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ON THE INSULATION OF HIGH TEMPERATURE
SEASONAL THERMAL STORAGE

J.F. Lane

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ON THE INSULATION OF HIGH TEMPERATURE
SEASONAL THERMAL STORAGE

ISOLATION DES RÉSERVOIRS DE STOCKAGE SAISONNIER DE
L'ÉNERGIE THERMIQUE À HAUTE TEMPÉRATURE

J. F. Lane

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T. R. Ringer, Head/Chef
Low Temperature Laboratory/
Laboratoire des basses températures

E. H. Dudgeon
Director/
Directeur

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ABSTRACT

This report reviews criteria to be met by an insulation for a seasonal thermal energy storage. The types of insulation available are reviewed and thickness of various insulations required to insulate various sizes of seasonal storages are calculated.

Non-evacuated fibrous insulation thicknesses are excessive for small (5m) diameter tanks, but may be acceptable for larger tanks. Evacuated insulations, either metal flake opacified fiber or metal foil plus spacers, are satisfactory for use at high temperatures (800°C). When using evacuated insulations provision must be made to prevent excessive external temperatures if the vacuum is lost.

RÉSUMÉ

Ce rapport étudie les critères auxquels doit satisfaire l'isolation des réservoirs de stockage saisonnier de l'énergie thermique. Divers isolants sont passés en revue ainsi que les épaisseurs appropriées d'isolant pour plusieurs diamètres de réservoir.

Les épaisseurs d'isolant en fibre sans vide sont excessives pour les petits réservoirs (5m de diamètre) mais sont acceptables pour les réservoirs plus grands. Les isolants avec vide, soit en fibres métalliques opacifiées soit en feuilles métalliques séparées par du vide, sont satisfaisants pour les hautes températures (800°C). Lorsqu'on utilise des isolants avec vide il faut éviter d'obtenir des températures extérieures excessives au cas où le vide n'existerait plus.

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SYMBOLS

Symbol		Unit
λ	Total number of layers of flake	
σ	Stefan-Boltzman constant = 5.6703×10^{-8}	W/m ² K ⁴
ϵ	Emissivity factor for foil insulations	
ϵ_1	Thermal emissivity of the hot side boundary	

CONTENTS (Cont'd)

Symbol	SYMBOLS (cont'd)	Unit
ϵ_2	Thermal emissivity of the cold side boundary	
A	Surface area of storage container	m^2
D	Diameter of storage = height of storage	m
E	Emissivity constant = $(1/\epsilon_1 + 1/\epsilon_2 - 1)$	
K_a	Overall thermal conductivity of insulation	w/mK
K_r	Radiation component of K_a	w/mK
K_s	Conductive component of K_a	w/mK
K_1	A factor used in calculation of k_s	
K_2	A factor used in calculation of K_r	
L	Allowable losses	% of capacity/year
n	Number of layers of flake per unit thickness	m^{-1}
Q	Thermal capacity of storage	W-hr
Q_L	Allowable thermal losses from storage	W
S	Unit storage capacity of storage media	kW-hr/ m^3
t_i	Thickness of insulation	m
T_1	Temperature of hotter surface	$^{\circ}C$
T_2	Temperature of colder surface	$^{\circ}C$
T_3	Mean temperature of insulation = $T_1 + T_2 / 2$	$^{\circ}C$
T_{1a}	Temperature of hotter surface	$^{\circ}K$
T_{2a}	Temperature of colder surface	$^{\circ}K$

ON THE INSULATION OF HIGH TEMPERATURE SEASONAL THERMAL STORAGE

1.0 INTRODUCTION

Seasonal thermal energy storages are attractive for some applications. They are essential for solar energy if it is to become a primary energy source. Without storage, solar energy, which is intermittent in nature, requires 100% back-up facilities to provide energy when the sun is not shining. Also, atomic power plants, which are constant energy producers, could use seasonal storage to supply energy for peak loads on a daily, weekly or monthly basis.

An essential part of thermal energy storage systems is the insulation of the containment vessel. A number of insulation systems are available such as fibrous insulation, powder, evacuated powder and evacuated multi-foil layers. This report examines some of the insulation requirements of thermal energy storage and the ability of various insulations to meet these requirements.

2.0 PERFORMANCE CRITERIA

The purpose of insulating a thermal storage is to reduce the heat leak to an acceptable level. As no seasonal thermal storages have been built, there are no existing standards available on which to gauge the performance of an insulation system. It thus becomes necessary to develop performance criteria before examining insulation performance.

Solar energy may be available for storage on a daily, a weekly, or a monthly basis. In northern climates there is considerably more energy available during summer months than winter months. Figure 1 shows the availability of direct incident solar energy for the Ottawa, Ontario area on a monthly basis. Only direct incident solar energy has been considered, as it is assumed that the storage will operate at a temperature that requires concentrating collectors, such as a parabolic trough or power tower, to collect the energy, and which collect only direct solar radiation.

The storage system will be required to supply energy on a daily basis to meet the night-time demands of society when the sun does not shine. The occurrence of several cloudy days in succession requires that the storage supply energy on a weekly basis. In northern climates the storage will receive energy in summer and deliver it in winter, thus creating a demand for storage on a seasonal basis. Much of the energy will reside in storage for six months or more, and the period of operation of the storage will be one year. It is thus desirable to examine performance on an annual basis.

For this investigation the following operating regime is assumed:

- (1) The storage operates at constant temperature, i.e. latent heat of fusion type.
- (2) Storage is full at time zero.
- (3) Energy withdrawn over 6-month period, i.e. storage is empty at time = 6 months.
- (4) Storage is refilled beginning at time = 6 months over a 6-month period, i.e. storage is full at time = 12 months.

With this type of operation the energy loss rate is constant with time. If the thermal losses are say 100% of capacity per year, then the losses during the first six months are 50% of capacity, leaving only 50% for other uses. To obtain this 50% for use it is necessary to collect 150% of capacity during the following six months, i.e. 50% for use plus 100% for one year's losses. The overall efficiency of the system is 33-1/3%, i.e. only one third of the energy calculated is available for use. The operating efficiencies for other loss rates are shown in Table 1. For general analysis purposes one can select a loss rate from the above table that gives an efficiency which would seem acceptable. The final selection will depend on a cost-benefit analysis which is beyond the scope of this report. For purposes of this report it is proposed to examine insulation thicknesses required to provide 60% efficiency and 74% efficiency or loss rates of 50% and 30% of capacity respectively. Insulation thicknesses for other efficiencies and loss rates can be inferred from this data.

3.0 INSULATION REQUIREMENTS

Some characteristics required of an insulation for use on storages are as follows:

- (1) acceptable thermal resistance
- (2) stable at operating temperatures
- (3) unaffected by contact with storage media
- (4) non-absorbent (water vapour, etc.)
- (5) non-flammable
- (6) non-toxic.

These characteristics are in general self-explanatory and will not be elaborated upon.

For purposes of this report it is proposed to examine insulation requirements for storages operating in the temperature range of 200 to 800°C. The lower limit of 200°C has been chosen as insulations for temperatures below this limit do not present any major problems. The upper limit of 800°C has been chosen as this represents the upper limit of technology for the containment vessel.

To simplify the calculation of the thickness of insulation required, a standard shape of containment vessel was assumed. This is the square cylinder, i.e. the height of the tank is equal to the diameter. Other shapes could have been chosen but this shape was chosen because of its simplicity for calculations. It is recognized that a square cylinder shape is not satisfactory for evacuated insulations where a cylinder with spherical ends or a sphere is preferred. Since a unidirectional heat flow equation is being used and the containers are, in general, large, it is felt that the shape of the vessel used in the calculations will not change the general conclusions.

4.0 THEORY

The thickness of the various insulations required was calculated using a very simplified one-dimensional formula of the form:

$$t_i = \frac{K_a (T_1 - T_2)}{Q_L / A} \quad (1)$$

It is admitted that this is not a rigorous treatment of insulation performance; however, it does give an indication of the thickness of insulation required and is satisfactory for a first evaluation of an insulation as applied to a high temperature storage.

The capacity of the storage is calculated using the equation:

$$Q = 1000 \frac{\pi}{4} D^3 S \quad (2)$$

The surface area of the containment vessel is

$$A = 1.5 \pi D^2 \quad (3)$$

when the shape is a square cylinder (height = diameter).

The allowable losses from storage are calculated using the equation:

$$\begin{aligned} Q_L &= \frac{Q}{365 \times 24} \text{ watts} \\ &= \frac{Q L}{876000} \text{ watts} \end{aligned} \quad (4)$$

Substituting equations 2, 3 and 4 in 1 and simplifying, we get:

$$t_i = \frac{5.256 \times 10^4 K_a (T_1 - T_2)}{D S L} \quad (5)$$

It is interesting to note that insulation thickness is an inverse function of tank diameter D , storage media unit capacity S and allowable losses L .

For purposes of this investigation, tank diameters between 5 and 30 m will be examined.

The value of S , the storage media unit capacity, depends on the storage media. Since the storage media is assumed to remain at a constant temperature, it follows that the storage system must be of the latent heat type. Kauffman and Lorsch [Ref. 1] have compiled data for a large number of materials which can be used for latent heat thermal storage. An examination of this data suggests that an average value for S is 200 kW hr/m^3 and values in excess of 300 kW hr/m^3 can easily be attained. For this report values of 200 and 300 kW hr/m^3 will be used for S .

5.0 CHARACTERISTICS OF INSULATIONS

The insulations available fall into three categories as follows:

- (1) Unevacuated fibrous insulations
- (2) Evacuated powder insulations
- (3) Evacuated multi-layer foil reflecting insulations.

Representative members of each of the above categories will be reviewed and thicknesses required to insulate various size storage tanks will be calculated. It should be noted that the calculations do not include thermal conduction losses for piping and supporting structure.

5.1 Fibrous Insulations

This type of insulation comprises a large number of randomly placed fibers which entrap air and prevent thermal losses by suppressing convection. Glass fiber insulation is one of the better known insulations in this family.

5.1.1 Fine glass fiber - no binder

This is the more common form of fibrous insulation. Typical K_a [Ref. 2] values for this insulation are as follows:

Mean Temperature °C	K_a (W/mK)
50	0.044
100	0.050
200	0.067
300	0.088
400	0.118
500	0.150
550	0.162

These values can be reduced to the following equation:

$$K_a = 0.04 + 7 \times 10^{-5} T_3 + 3 \times 10^{-7} T_3^2 \quad (6)$$

$$\text{where } T_3 = \text{mean temperature} = \frac{T_1 + T_2}{2} \quad (7)$$

The maximum operating temperature is 1000°C.

Figures 3, 4, 5 and 6 show the estimated insulation thickness for a storage with a storage media whose capacity is 200 or 300 kW-hr/m³ and an annual loss rate of 50% or 30% of capacity.

5.1.2 Alumina-silica fiber plus binder

Typical K_a values [Ref. 2] for this insulation are as follows:

Mean Temperature °C	K_a (W/mK)
200	0.058
300	0.074
400	0.091
500	0.106
600	0.122
650	0.130

These values can be reduced to the following equation:

$$K_a = 0.026 + 1.6 \times 10^{-4} T_3$$

$$\text{where } T_3 \text{ is the mean temperature } T_3 = \frac{T_1 + T_2}{2} \quad (8)$$

The maximum operating temperature is 1300°C.

Figures 7, 8, 9 and 10 show the estimated insulation thickness for a storage with a storage media whose capacity is 200 or 300 kW-hr/m³ and an annual loss rate of 50 and 30% of capacity.

5.1.3 Foam glass

Foam glass is a closed cell inorganic foam and is usually formed into a rigid board with a compressive strength of 500 to 700 kPa. It has a melting temperature near 820°C. It is impervious to most acids, caustics and solvents.

Typical K_a values [Ref. 2] for this insulation are as follows:

Mean Temperature °C	K_a (W/mK)
50	0.055
100	0.063
150	0.073
200	0.085
250	0.095

These values can be reduced to the following equation:

$$K_a = 0.0463 + 1.4 \times 10^{-4} T_3 + 2.667 \times 10^{-7} T_3^2 \quad (9)$$

Maximum operating temperature is 425°C.

Figures 11, 12, 13 and 14 show the estimated insulation thickness for a storage with a storage media whose capacity is 200 or 300 kW-hr/m³ and an annual loss rate of 50 or 30% of capacity.

Foam glass can be used either as an external load bearing insulation or as an internal insulation. When used as an internal insulation it reduces the temperature at which the stressed shell of the containment vessel operates. It may thus be possible to use a lower cost material for the shell.

The low maximum operating temperature (425°C) limits the selection of the storage media which can be used with it. Other types of solid foams such as refractory brick might be considered for use at higher operating temperatures.

5.2 Evacuated Powder or Fiber

Evacuated powder insulations consist of either a powder or a fiber sealed in an evacuated space enclosing the object to be insulated. The powder is evacuated to a pressure of 10⁻³ torr or lower. Evacuation of the space eliminates conduction losses by the interstitial gas.

The fiber or powder may be impregnated with aluminum, copper or nickel flakes, to act as reflective barriers. This type of insulation is generally non-load bearing. Heat loss through the insulation is by thermal conduction through the fibers or powder or by radiation.

The thermal conductance K_a is expressed as:

$$K_a = K_s + K_r \quad (10)$$

$$K_s = K_1 \left(\frac{T_1^{3/2} - T_2^{3/2}}{T_1 - T_2} \right) \quad (11)$$

$$K_r = K_2 \left(\frac{T_1^4 - T_2^4}{T_1 - T_2} \right) \quad (12)$$

The factors K_1 and K_2 are specific to each type of insulation.

5.2.1 Evacuated powder with glass fiber

Reiss [Ref. 3] has examined the use of an evacuated powder insulation with the following composition:

Fumed silica	10 weight parts
Fe_3O_4	1 weight part
TiO_2	1 weight part
Glass fibers	10% by weight of powder

The glass fibers have a diameter of 13 μm and a length of 1 to 5 mm.

This insulation can withstand a compressive load of 650 kPa and can therefore be used to support the containment vessel if it is not too large.

Typical K_a values for this insulation are as follows:

Hot Side Temperature °C	K_a (W/mK)
283	0.00768
318	0.00832
350	0.0088
380	0.00944

These values can be expressed with the following relationship:

$$K_a = 2.3 \times 10^{-3} + 2.0 \times 10^{-5} T_1 - 2.29 \times 10^{-9} T_1^2 \quad (13)$$

where T_1 = hot side temperature.

The maximum operating temperature is about 400°C.

The insulation must be evacuated to 1×10^{-3} torr.

Figures 15, 16, 17 and 18 show estimated insulation thicknesses required for a storage with a storage media capacity of 200 or 300 $kg-hr/m^3$ and annual losses of 50 and 30% of capacity.

5.2.2 Aluminum opacified glass fiber

This is an evacuated insulation in which the evacuated space is filled with glass fibers which have been impregnated with

aluminum flakes to make the fibers opaque to radiation. It will carry compressive loads up to 100 kPa. Grunert, Notaro and Reid [Ref. 4] have established the following thermal conductivity relationships for this type of insulation:

$$K_1 = 1.4758 \log n - 5.9497 \times 10^{-4} \quad (14)$$

$$K_2 = 0.5778 \sigma \frac{\lambda}{n} \left[\frac{1}{E + \frac{\lambda}{n} (0.15 n + 39370)} \right] \quad (15)$$

$$K_a = K_1 \left(\frac{T_1^{3/2} - T_2^{3/2}}{T_1 - T_2} \right) + K_2 \left(\frac{T_1^4 - T_2^4}{T_1 - T_2} \right) \quad (16)$$

$$\text{Insulation thickness } t_i = \frac{\lambda}{n} \quad (17)$$

Layer density n is typically 10,800 to 21,600 layers per metre.

Maximum operating temperature is 425°C.

Figures 19, 20, 21 and 22 show the estimated insulation thickness for a storage with a storage media capacity of 200 or 300 kW-hr/m³ and annual losses of 50% and 30% of capacity. The calculated thicknesses are based on the following emissivity values.

containment vessel $\epsilon_1 = 0.35$ (18-8 stainless steel)
insulation container $\epsilon_2 = 0.11$ (dull nickel plate)

Layer density was assumed at 15,000 layers per metre.

5.2.3 Nickel opacified, reffrasil-quartz fiber insulation

This is an evacuated insulation in which the evacuated space is filled with reffrasil quartz fibers which have been opacified with nickel flakes. This insulation will carry compressive loads up to 100 kPa. Grunert, Notaro and Reid [Ref. 4] established the following thermal conductivity relationships for this type of insulation as follows:

$$K_1 = (0.67 \log n - 2.2) \times 10^{-4} \quad (18)$$

$$K_2 = 0.5778 \frac{\sigma \lambda}{n} \left[\frac{1}{E + \frac{\lambda}{n} (5.5 n - 5315)} \right] \quad (19)$$

$$K_a = K_1 \left(\frac{T_1^{3/2} - T_2^{3/2}}{T_1 - T_2} \right) + K_2 \left(\frac{T_1^4 - T_2^4}{T_1 - T_2} \right) \quad (20)$$

Insulation thickness, $t_i = \lambda/n$

Layer density, n , is typically 2100 to 4300 layers per metre.

The maximum operating temperature is 800°C.

Figures 23, 24, 25 and 26 show the estimated insulation thickness for a storage with a storage media capacity of either 200 or 300 kW-hr/m³ and annual losses of 50% and 30% of capacity. The calculated thicknesses are based on the following emissivity values:

containment vessel $\epsilon_1 = 0.35$ (18-8 stainless steel)
insulation container $\epsilon_2 = 0.11$ (dull nickel plate)

Layer density was assumed at 3000 layers per metre.

5.3 Multi-Foil Evacuated Insulation

A multi-foil evacuated insulation consists of a number of alternate layers of thin, highly reflective metallic foils oriented normal to the direction of heat flow and glass or quartz paper spacers. The insulation is evacuated. This type of insulation is known as "Super Insulation". The metallic foils are usually molybdenum, nickel, copper or aluminum. The choice of foil is often dependent on the maximum operating temperature. Two or three different foils may be used in a built-up insulation with say aluminum being used in the outer layers where temperatures are cool, and another material such as nickel in the inner layers where the temperatures are high. In general each insulation is designed to suit the application.

The spacer may be woven zirconia cloth, woven quartz cloth, quartz paper, nickel, copper or aluminum opacified glass paper or glass paper. Again the spacer material may vary throughout the thickness of the insulation with say glass paper, in the outer, cooler layers and quartz or zirconia cloth in the inner, very hot layers.

The operating temperatures of a number of materials used for multi-foil insulation systems are given in Table 2.

The foil is evacuated to a pressure of 10^{-3} torr or lower.

The thermal conductivity K_s of multi-foil insulations is made up of two parts - a conductive portion K_g and a radiative portion K_r . The conductive portion, K_g , is calculated using the following relationship:

$$K_g = K_1 \left(\frac{T_1^{3/2} - T_2^{3/2}}{T_1 - T_2} \right) \quad (21)$$

The radiative portion, K_r , is calculated using the following relationship:

$$K_r = K_2 \left(\frac{T_1^4 - T_2^4}{T_1 - T_2} \right) \quad (22)$$

The constants, K_1 and K_2 , are specific to each type of insulation.

5.3.1 Nickel foil-refrasil quartz paper insulation

This type of insulation consists of thin foils of nickel alternating with a refrasil quartz paper spacer. Layer densities may vary between 3300 and 7000 layers per metre. The insulation can stand low compressive loads up to about 40 kPa.

Notaro, Nies and Hedel [Ref. 5] have established the following relationships for its thermal conductivity:

$$K_1 = [0.859 \log n - 3.006] \times 10^{-4} \quad (23)$$

$$K_2 = [1.59 \times 10^{-8}] \epsilon/n \quad (24)$$

$$\text{and } \epsilon = 0.000144 T_1 + 0.000033 n - 0.137 \quad (25)$$

n = number of layers of foil per metre.

The layer density n is typically 3300 to 7000 layers per metre.

Maximum operating temperature is 950°C.

Figures 27, 28, 29 and 30 show the estimated insulation thicknesses for a storage with storage media capacities of 200 or 300 kW-hr/m³ and 50% or 30% annual losses. Layer density was assumed at 5000 layers per metre.

6.0 GENERAL COMMENTS ON INSULATIONS

The nature of the heat loss equations is such that if the tank dimension (diameter) is doubled, the insulation thickness is reduced by a factor of 2. It follows that the larger the tank the thinner the insulation.

Similarly, if the tank size is held constant and the capacity (S) of the storage media is increased, the insulation thickness can be reduced and still maintain the same losses when expressed as a percentage of total storage capacity.

The above two characteristics combine to produce a trend towards the use of very large storage containers with the highest capacity storage media consistent with good economics.

A comparison of the thickness of various insulations required to insulate a 10 m dia. tank when operating at 200, 400, 600 and 800 C is shown in Table 3. This table shows the relative merits of the various insulations.

Evacuated insulations are very thin and are particularly useful for the higher temperatures where the thickness of the non-evacuated insulations becomes excessive.

Table 3 was developed for a specific tank diameter, a storage media capacity of 200 kW-hr/m³ and 30% annual losses. Changes in any of these parameters will have a corresponding change in the thickness of insulation required.

The use of evacuated insulations requires that the insulation be enclosed in a vacuum-tight jacket and that vacuum pumps be available for periodically evacuating the insulation. The added complications and expense of the enclosure and vacuum pumps may make them uneconomical. Further, if the vacuum is lost, a safety hazard may develop when the outer jacket heats up from increased heat losses.

Insulation thickness calculations have been based on 30% and 50% annual losses corresponding to storage efficiencies of 74 and 60% respectively. These calculations do not include losses for connecting piping and containment vessel supports. In making a preliminary assessment of insulation thickness it would be desirable to use the thicknesses given for 30% annual losses as a first estimate to provide some compensation for the losses through connecting piping and container supports.

7.0 CONCLUSIONS

A number of insulations are available for effectively insulating seasonal thermal energy storages. The nature of the insulations and the losses tend toward the use of very large diameter tanks and high capacity storage media.

Non-evacuated insulations are satisfactory for insulating lower temperature (200 to 400°C) storages but the thickness becomes excessive for higher temperature storages unless the size is very large (20 to 30 m dia.).

Evacuated insulations are satisfactory for all storage temperatures. A hazard exists if the vacuum is lost and the outer jacket heats up from excessive heat losses.

This report gives an indication of the thickness of various types of insulation required to insulate a seasonal storage. The final selection of the insulation must be based on a cost-performance analysis done at the time of construction of the storage. Insulation systems other than those described here are available which may perform better and lead to different conclusions.

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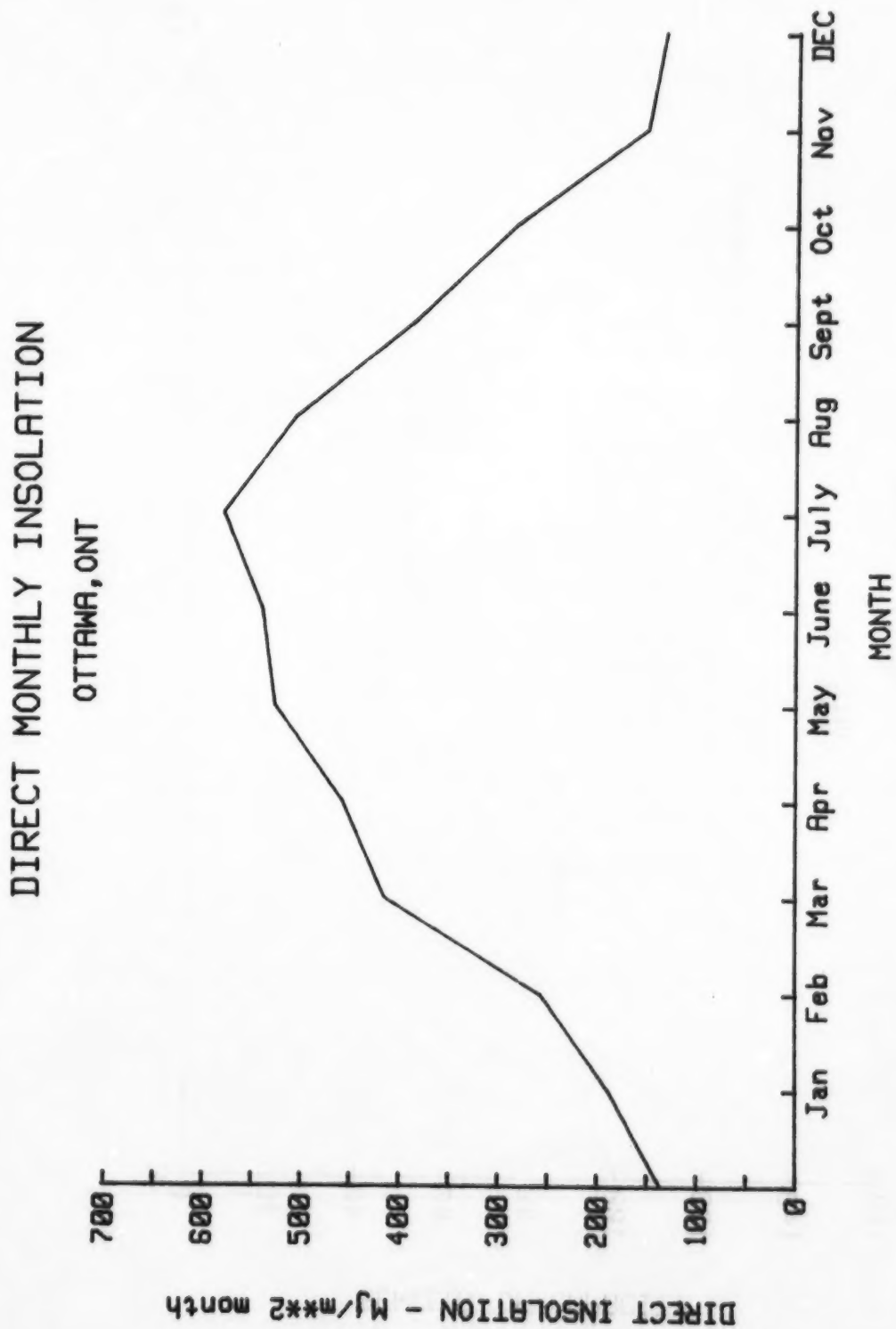


Fig. 1 Availability of Direct Incident Solar Radiation in the Ottawa Ontario Area

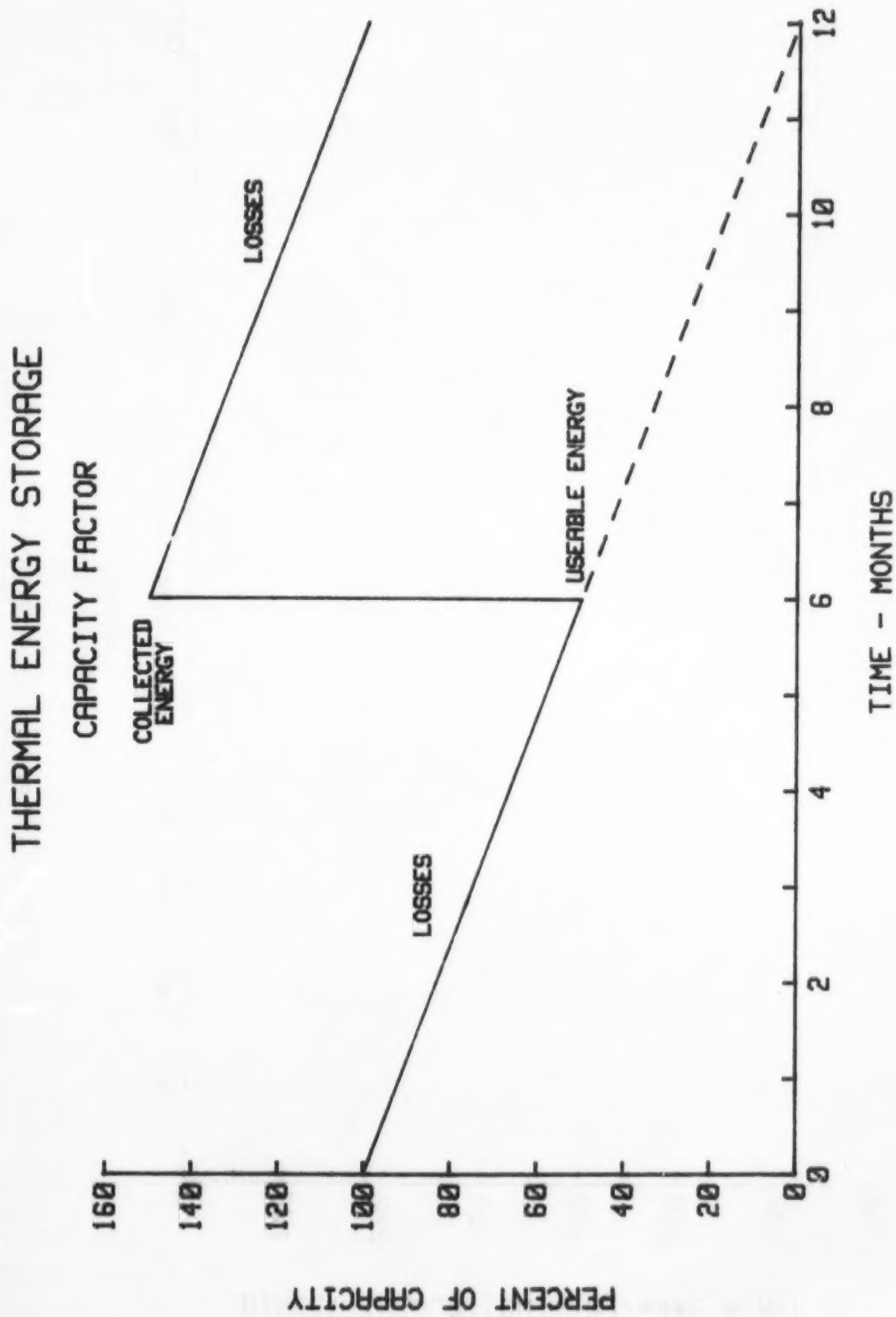


Fig. 2 Capacity Factor for a Storage with Losses of 100% of Capacity per Year

THERMAL ENERGY STORAGE INSULATION

GLASS FIBER-NO BINDER

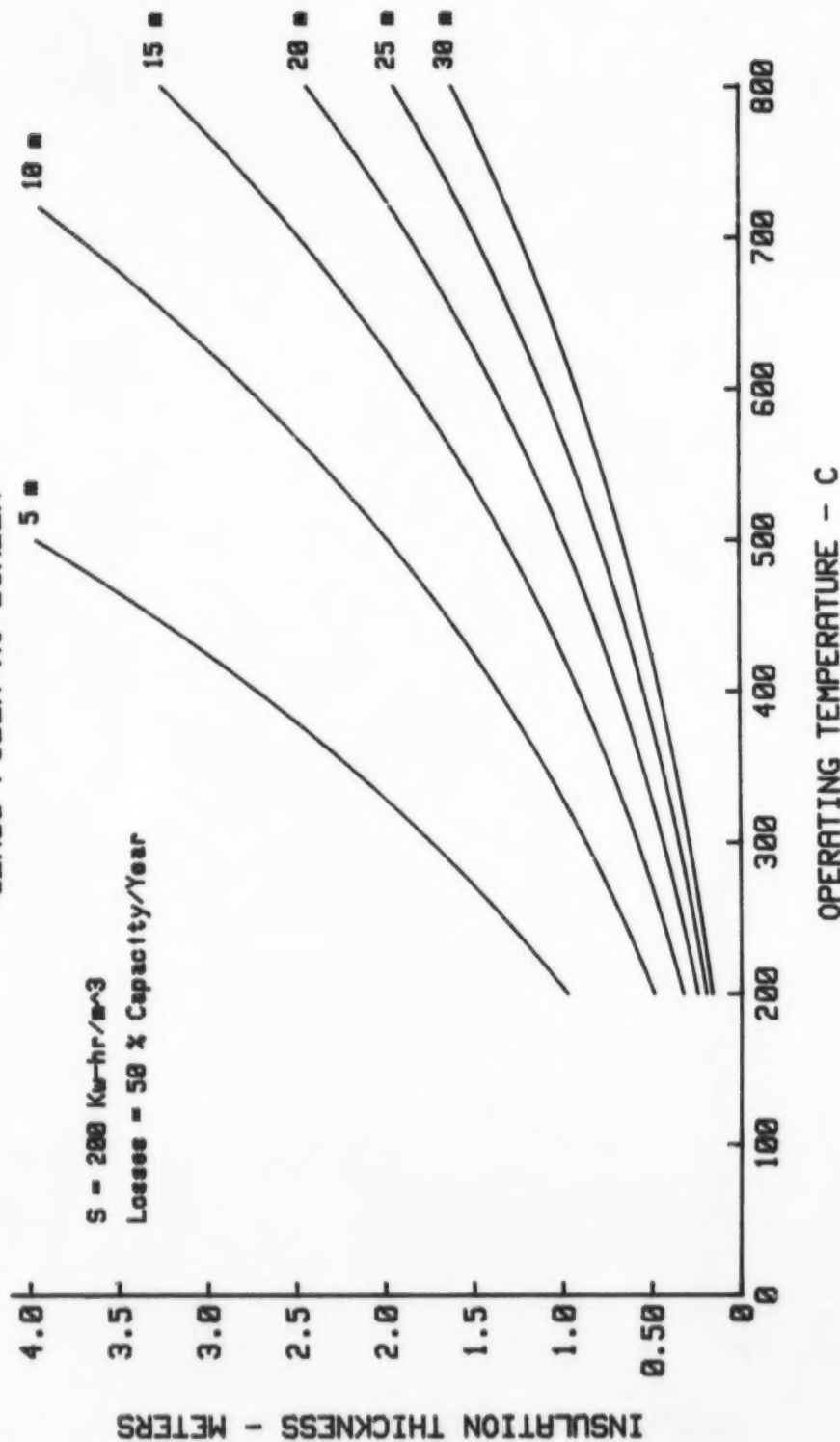


Fig. 3 Thickness of Glass Fiber - No Binder Insulation Required
 for a Seasonal Storage with 50% Annual Losses and a Storage
 Media Capacity of 200 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION

GLASS FIBER-NO BINDER

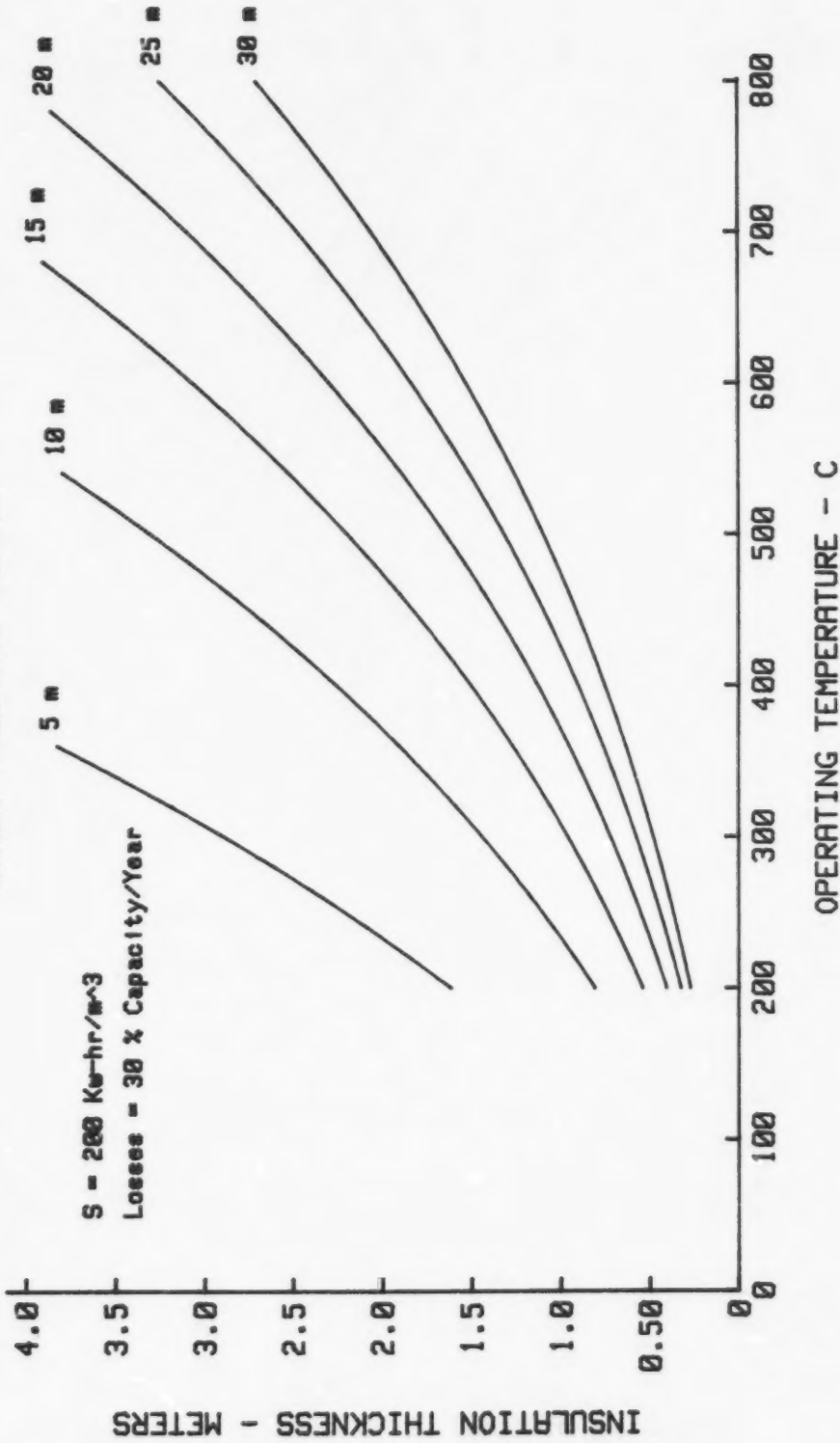


Fig. 4 Thickness of Glass Fiber - No Binder Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 200 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION GLASS FIBER-NO BINDER

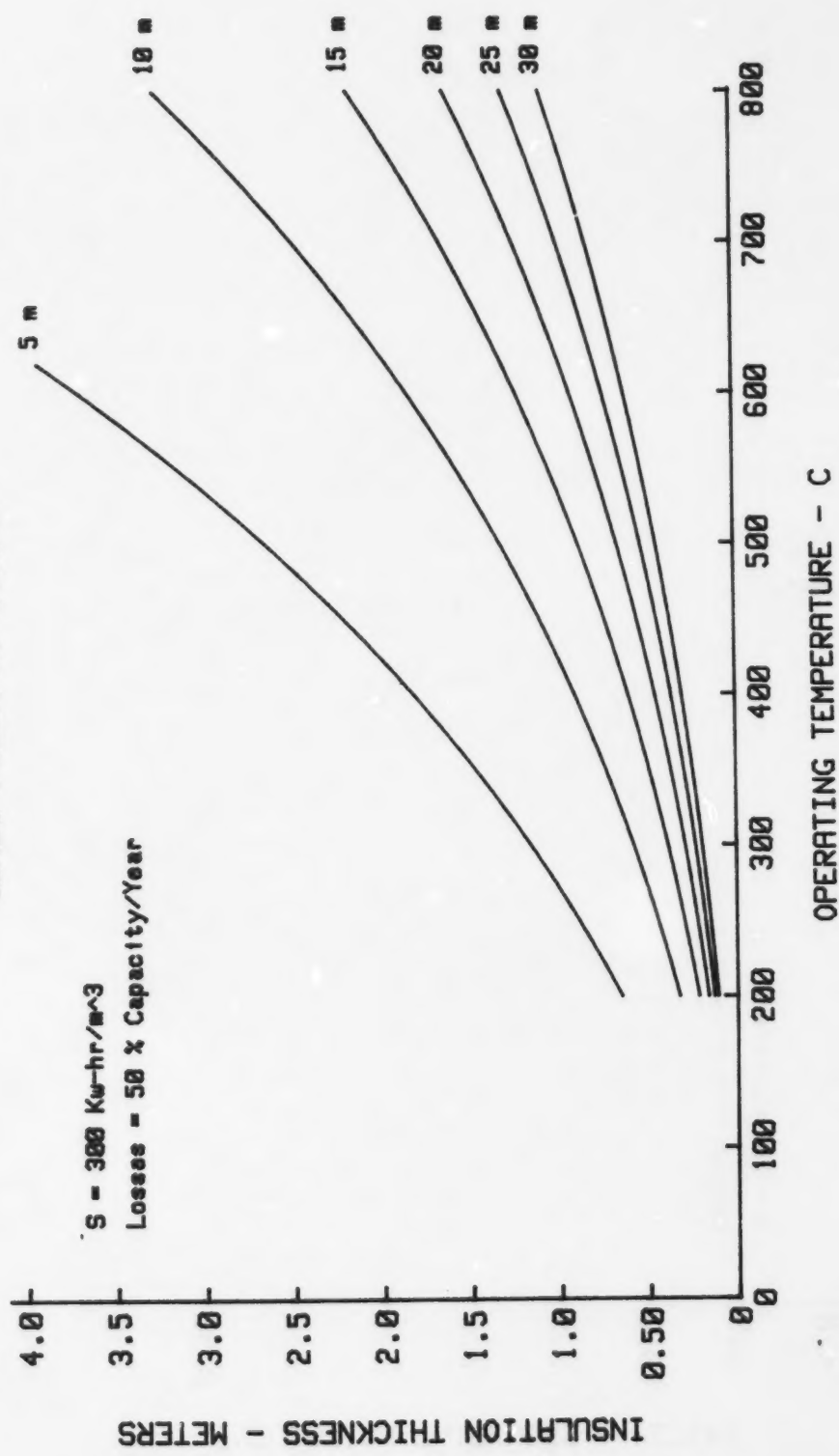


Fig. 5 Thickness of Glass Fiber - No Binder Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 300 kw-hr/m³

THERMAL ENERGY STORAGE INSULATION

GLASS FIBER-NO BINDER

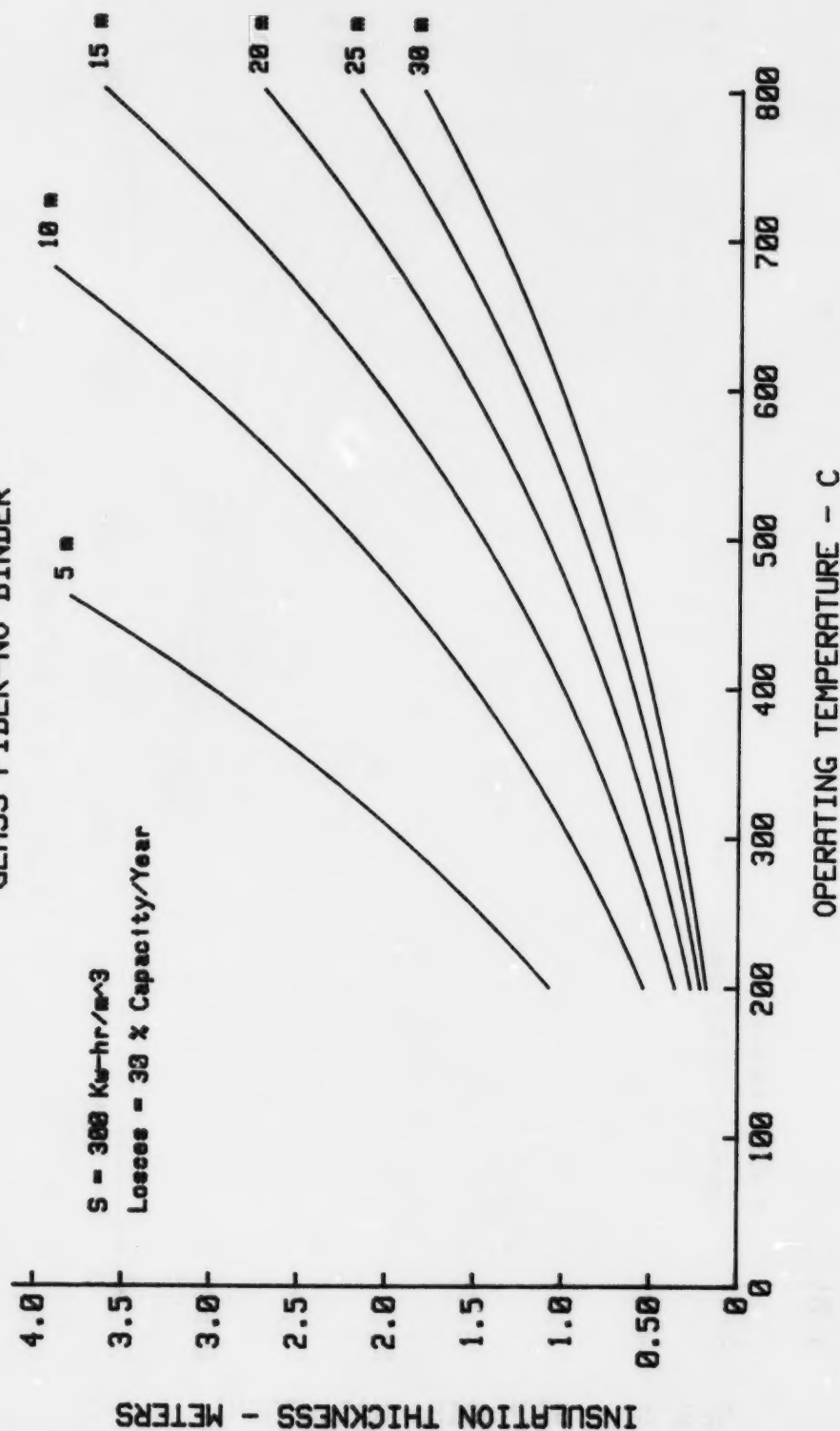


Fig. 6 Thickness of Glass Fiber - No Binder Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 300 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION

ALUMINA-SILICA FIBER + BINDER

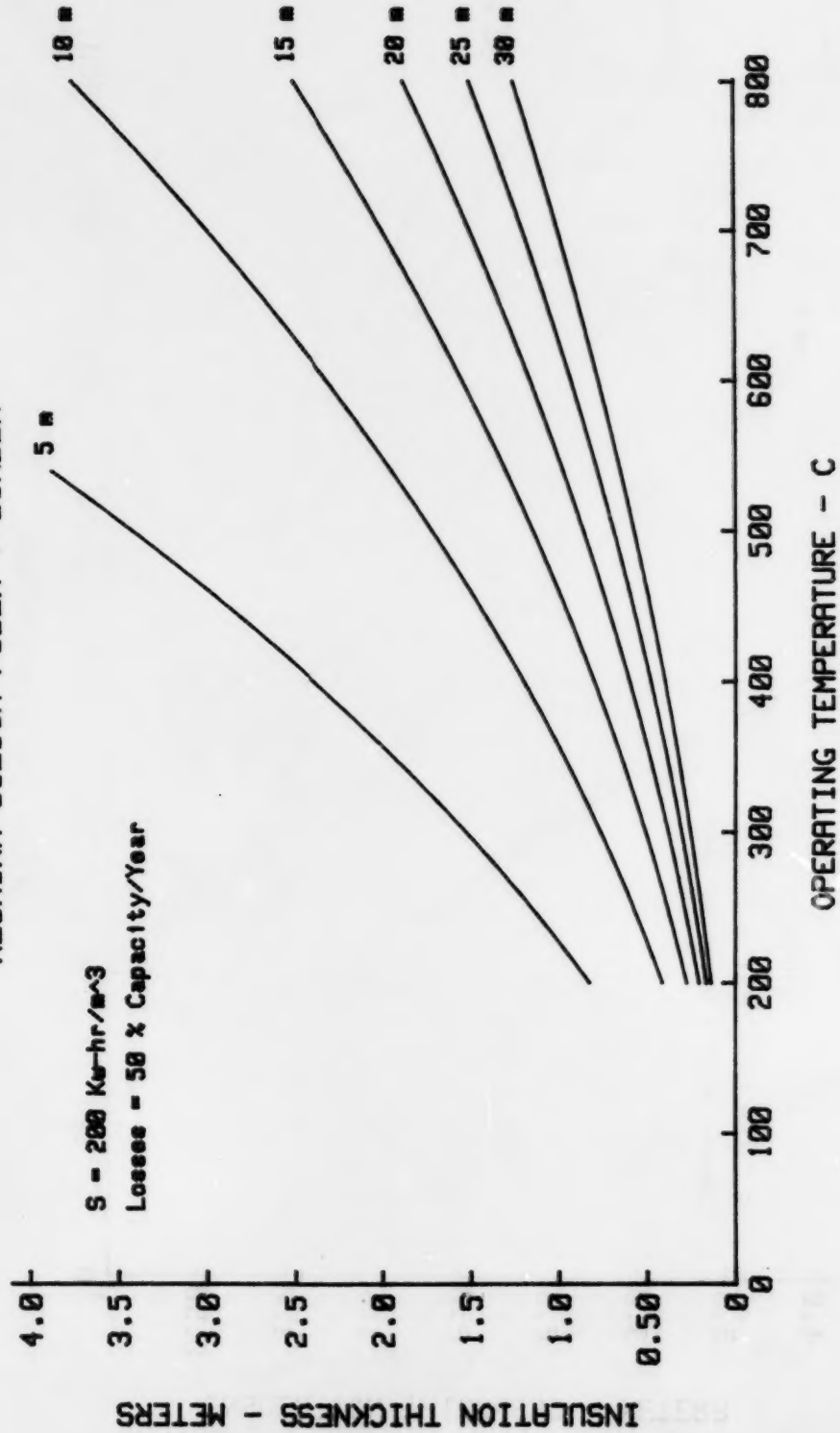


Fig. 7 Thickness of Alumina-Silica Fiber plus Binder Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 200 kW-hr/m²

THERMAL ENERGY STORAGE INSULATION

ALUMINA-SILICA FIBER + BINDER

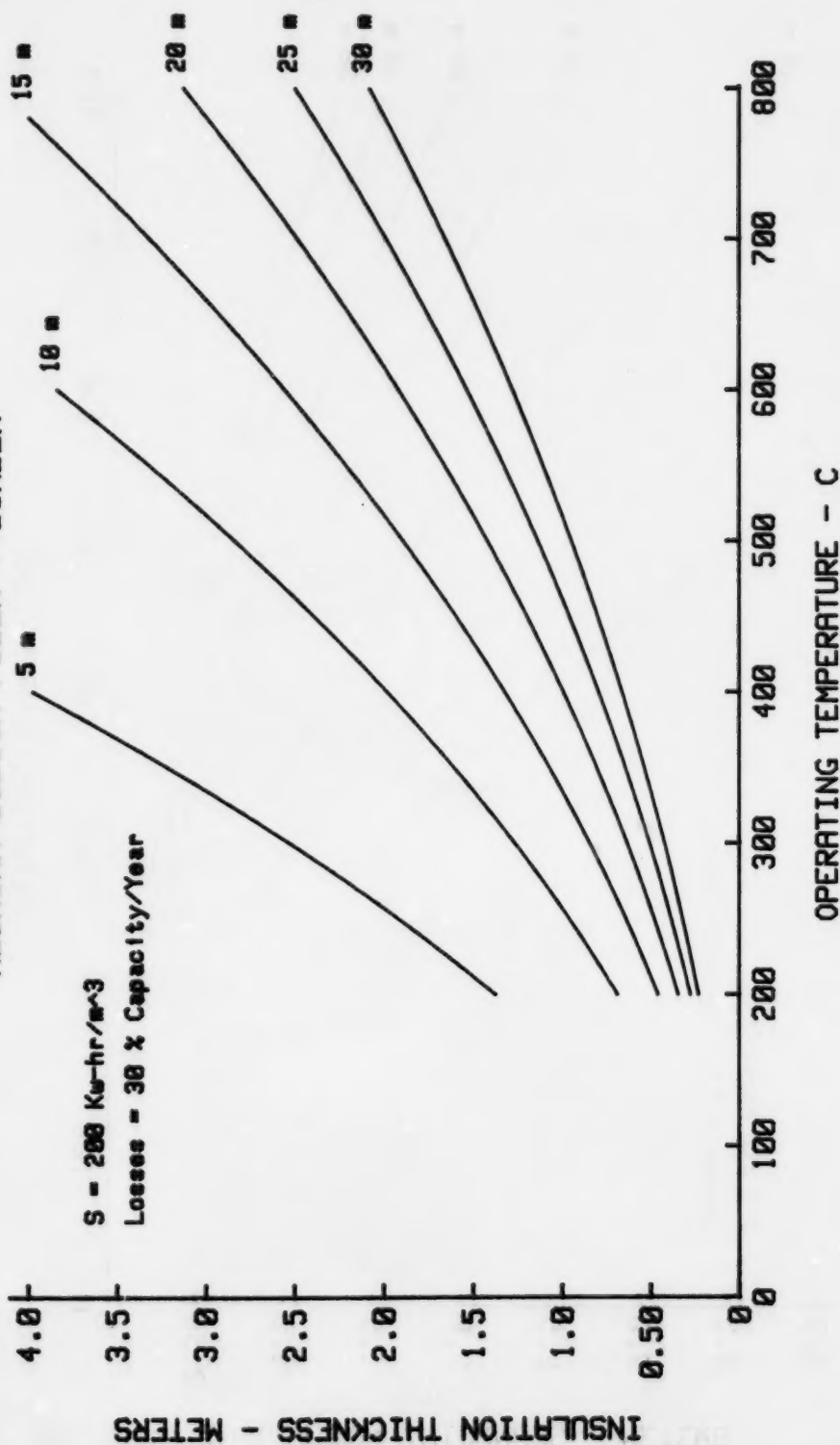


Fig. 8 Thickness of Alumina-Silica Fiber plus Binder Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 200 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION ALUMINA-SILICA FIBER + BINDER

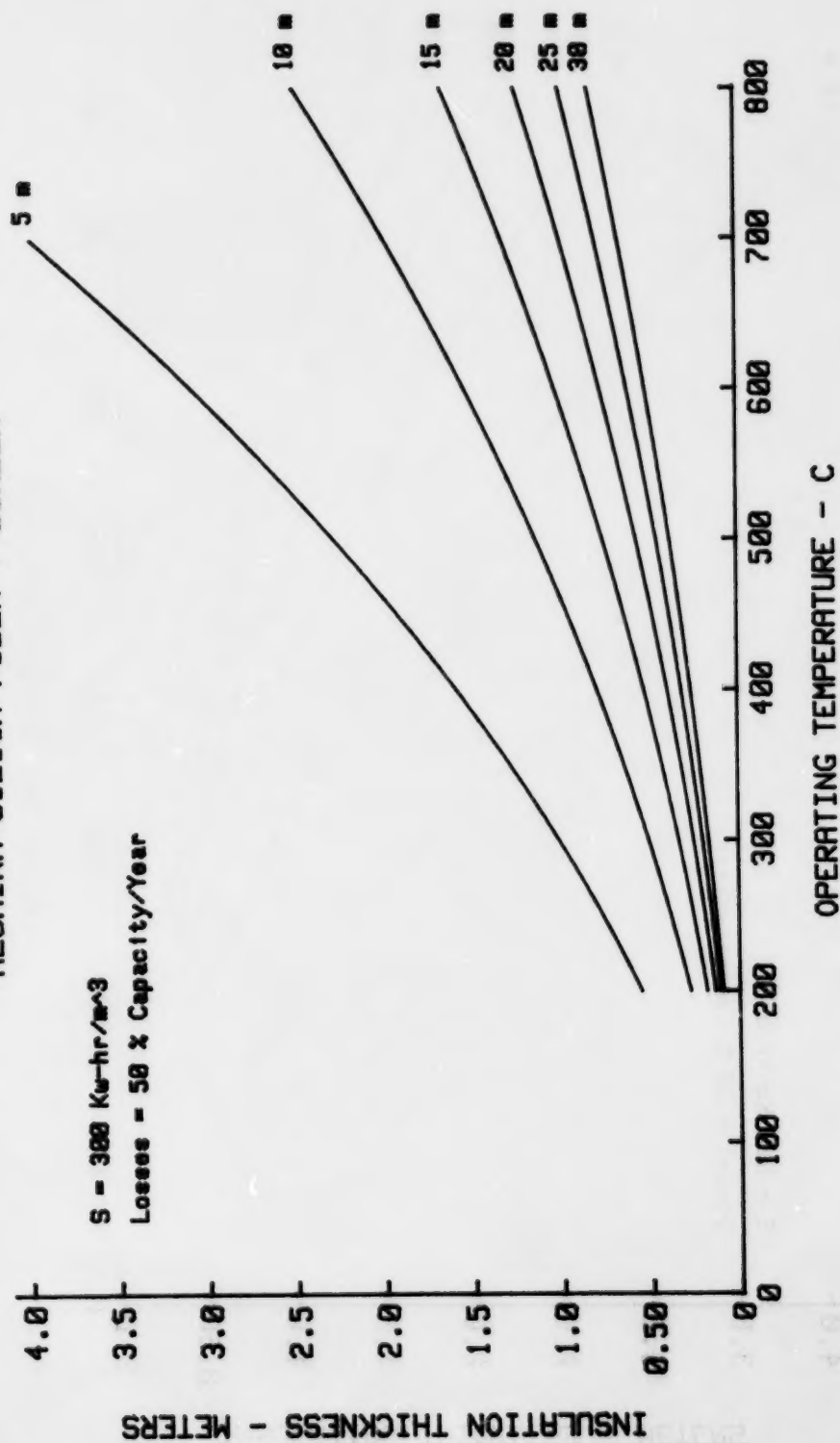


Fig. 9 Thickness of Alumina-Silica Fiber plus Binder Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 300 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION ALUMINA-SILICA FIBER + BINDER

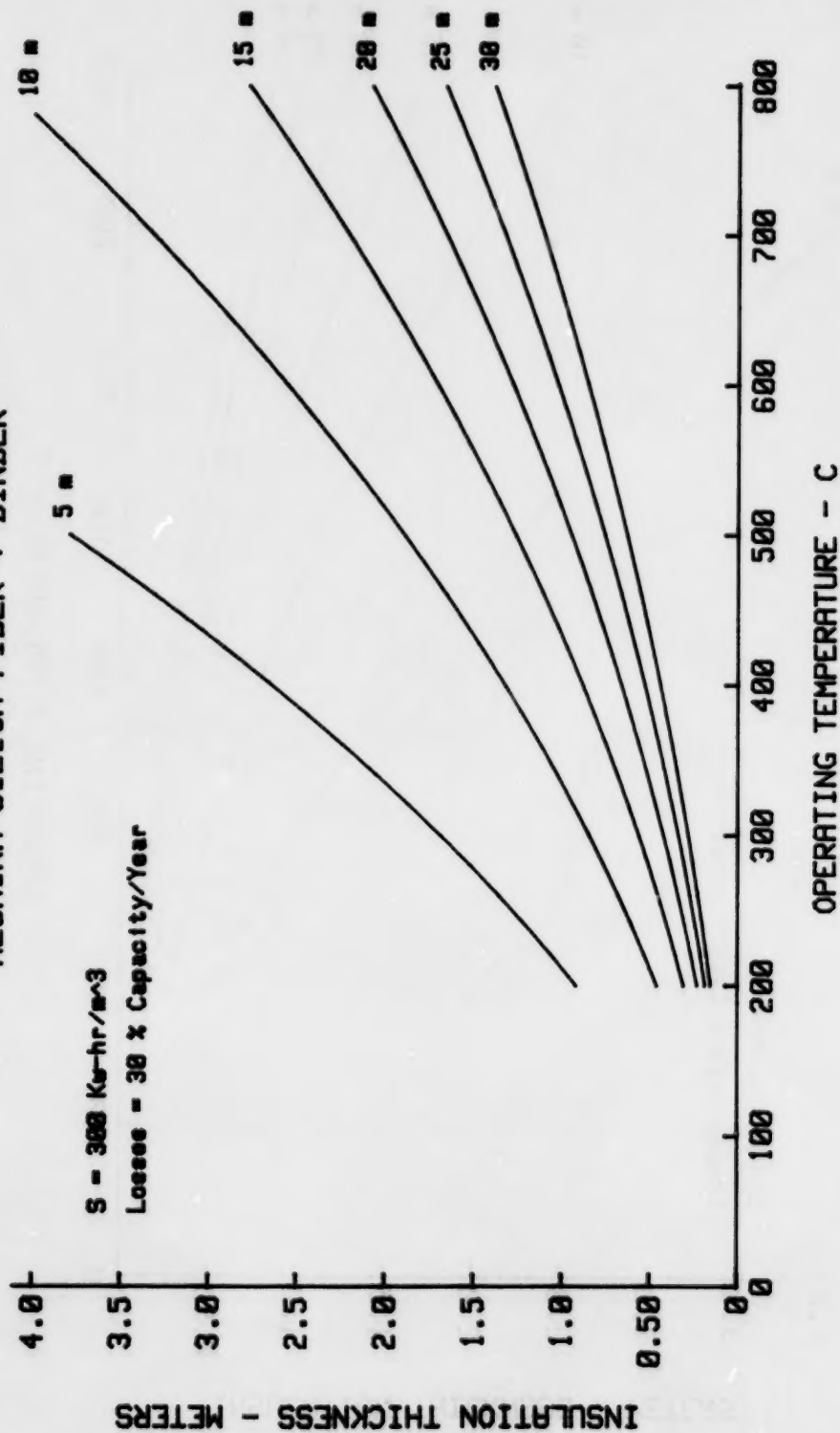


Fig. 10 Thickness of Alumina-Silica Fiber plus Binder Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 300 Kw-hr/m³

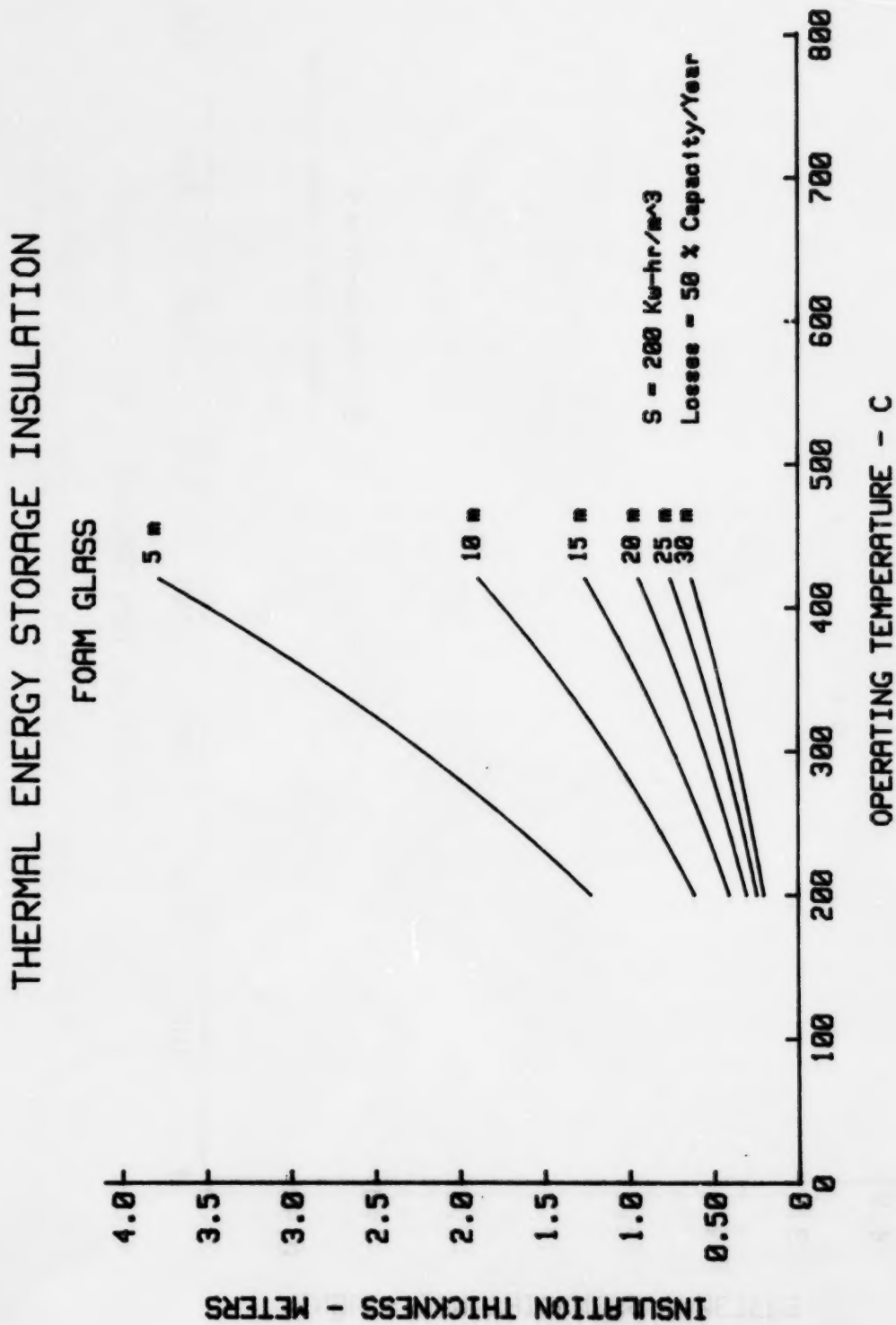


Fig. 11 Thickness of Foam Glass Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 200 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION

FOAM GLASS

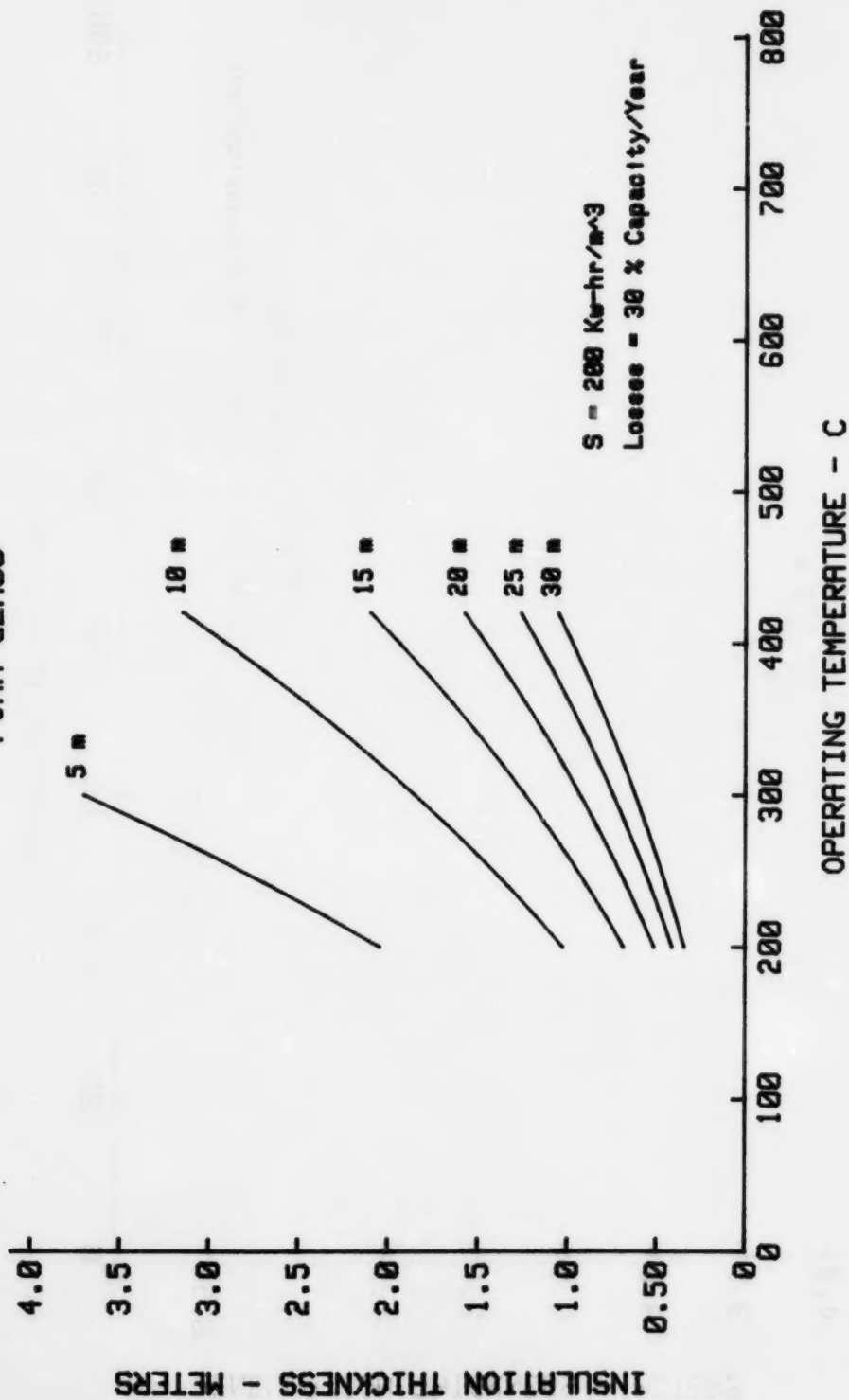


Fig. 12 Thickness of Foam Glass Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 200 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION FOAM GLASS

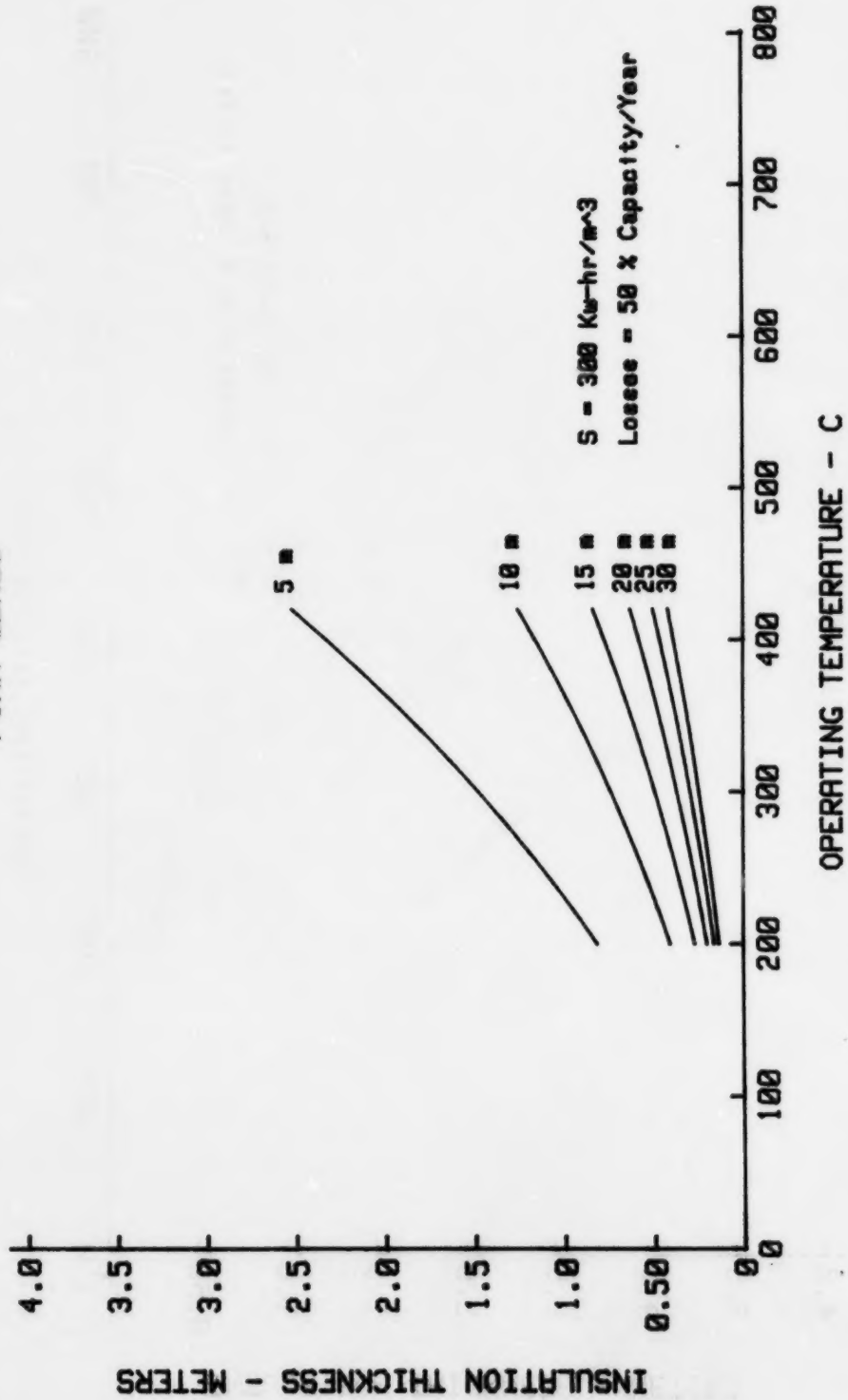


Fig. 13 Thickness of Foam Glass Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 300 $kW-hr/m^3$

THERMAL ENERGY STORAGE INSULATION

FOAM GLASS

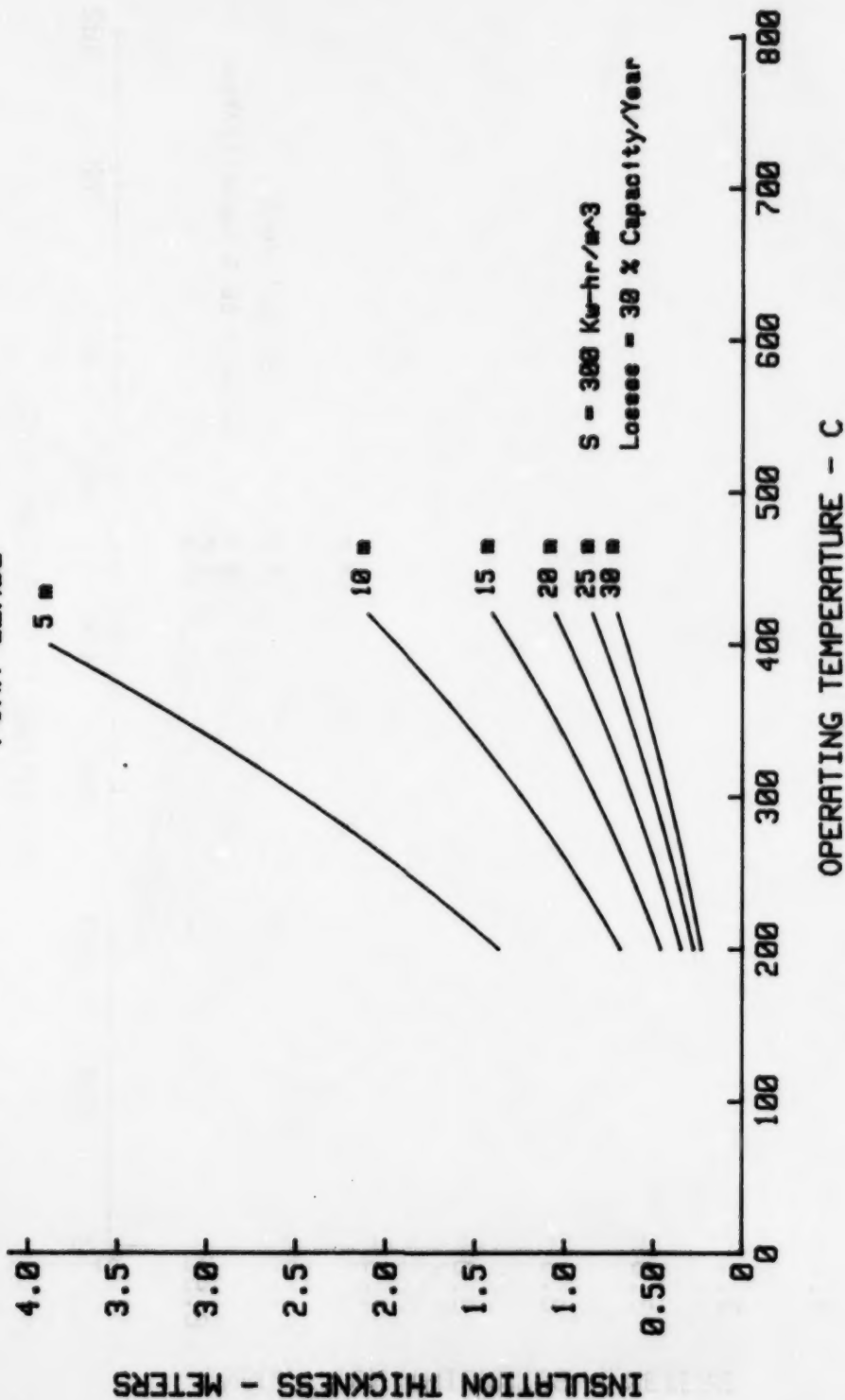


Fig. 14 Thickness of Foam Glass Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 300 kw-hr/m³

THERMAL ENERGY STORAGE INSULATION EVACUATED POWDER

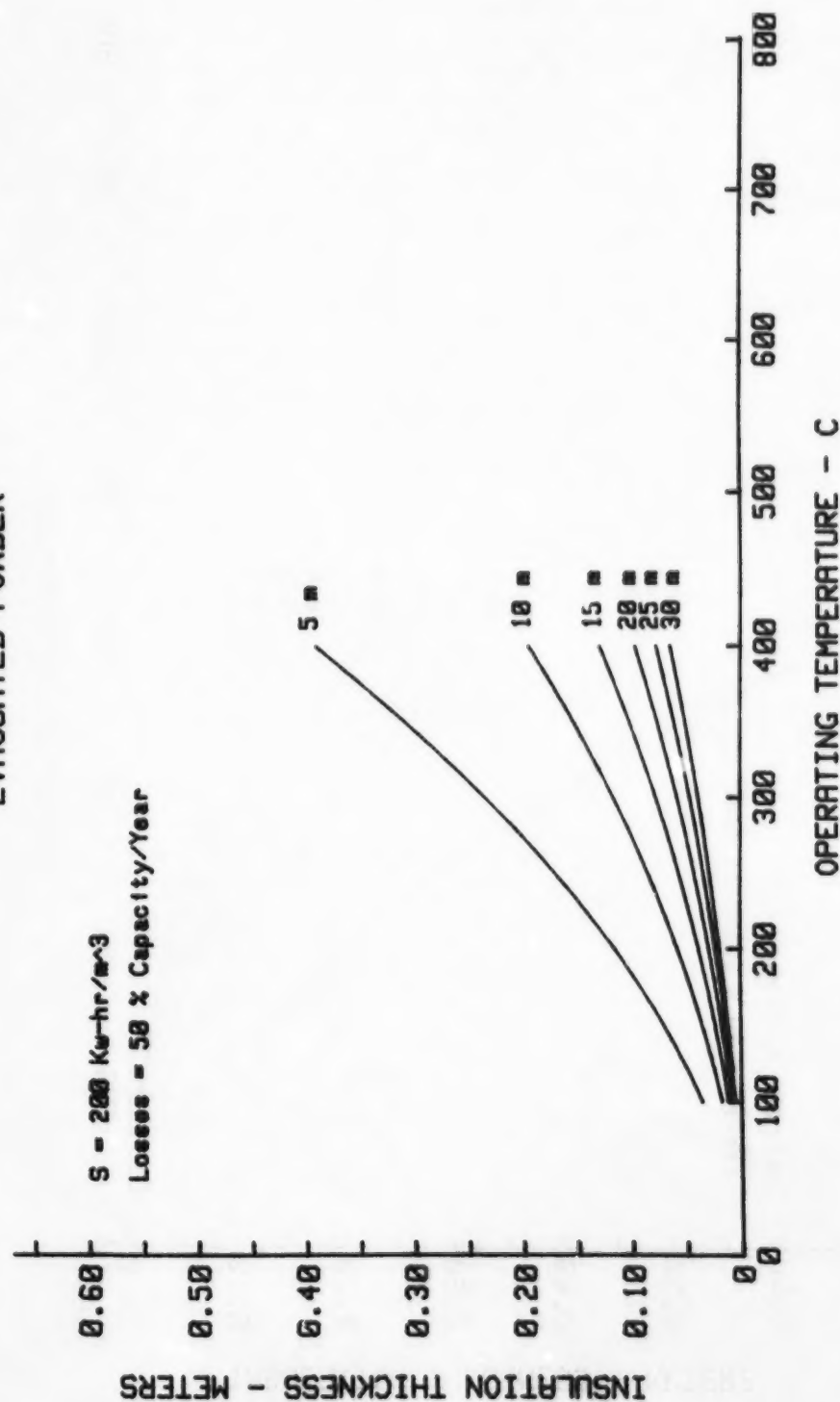


Fig. 15 Thickness of Evacuated Powder Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 200 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION

EVACUATED POWDER

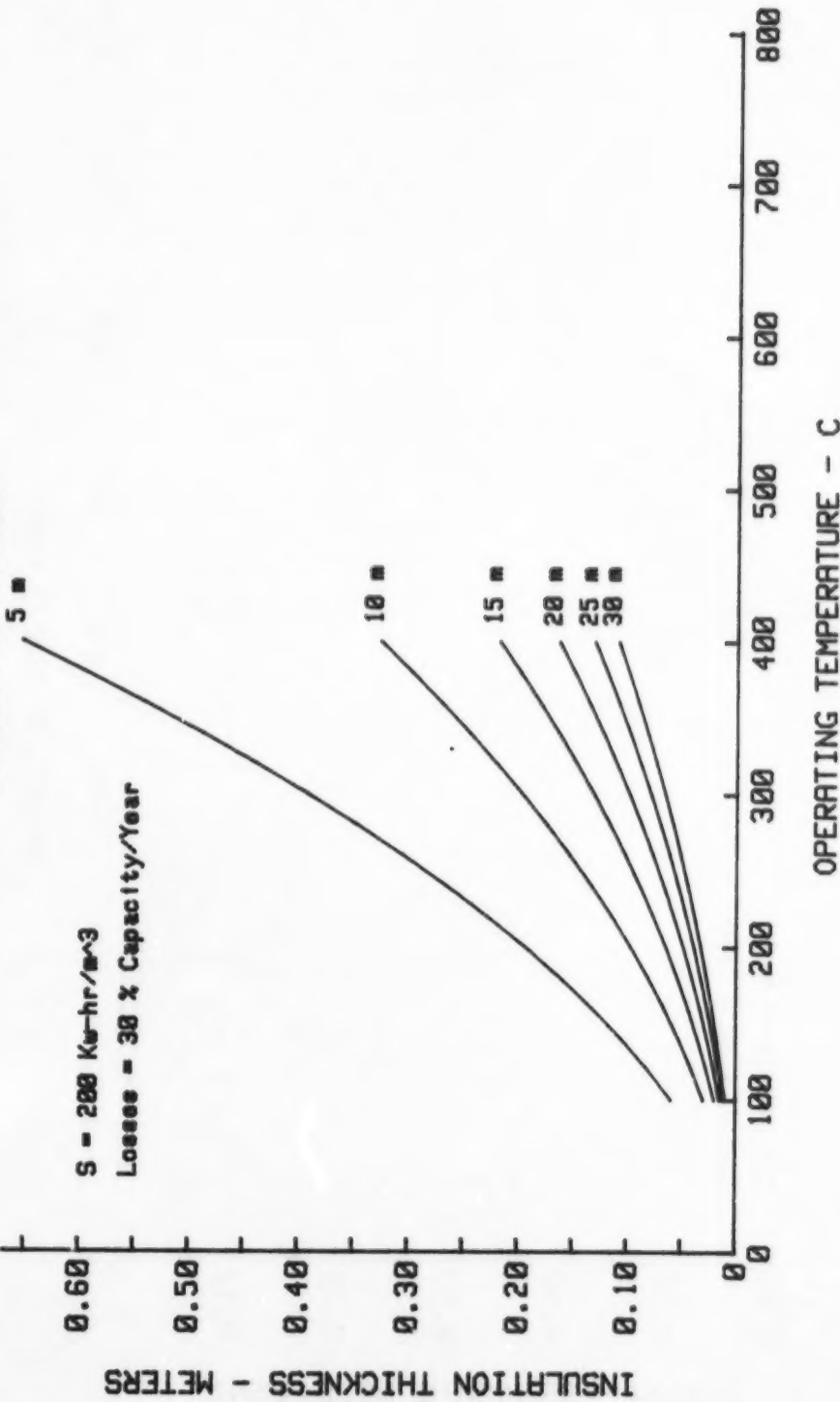


Fig. 16 Thickness of Evacuated Powder Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 200 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION EVACUATED POWDER

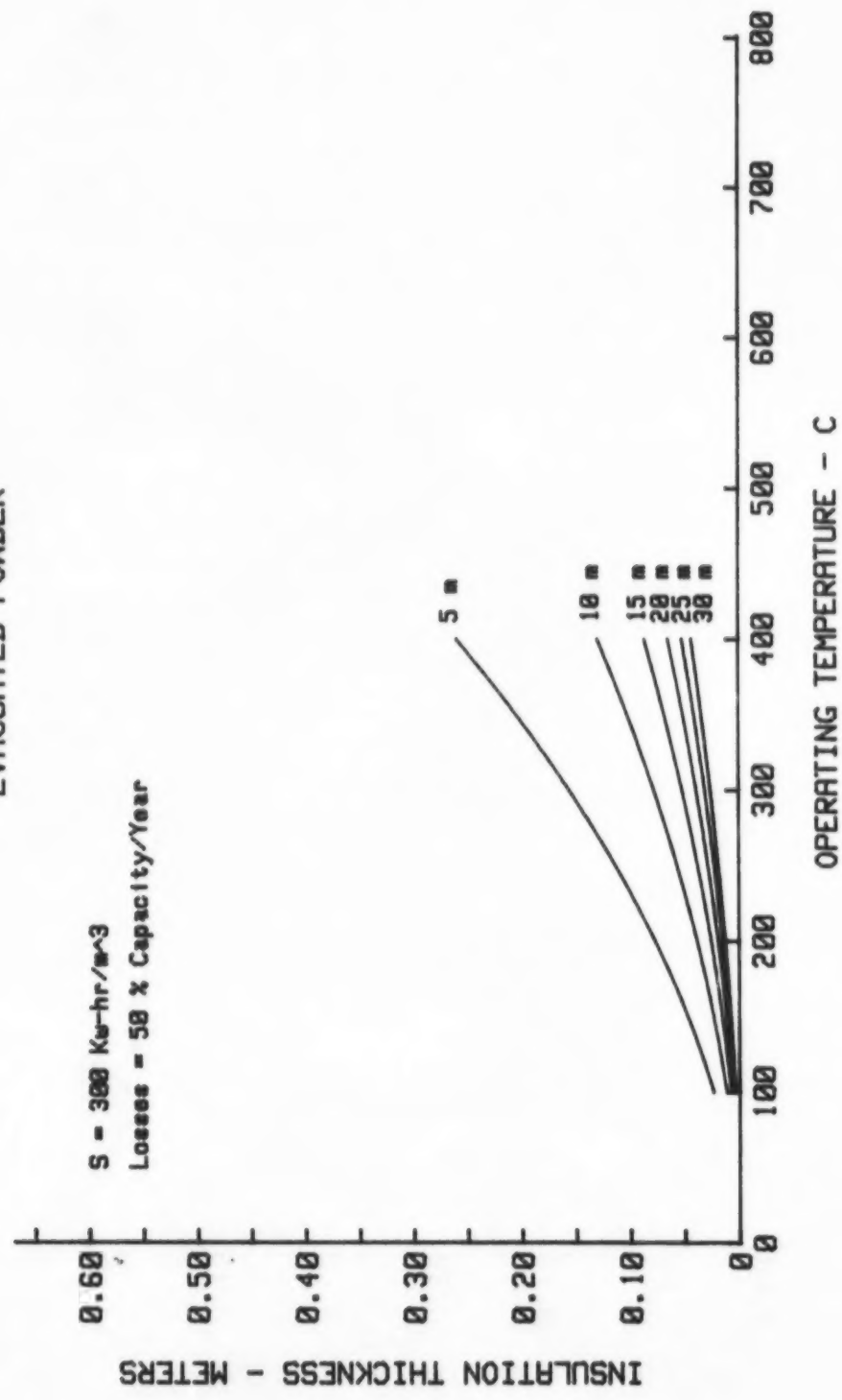


Fig. 17 Thickness of Evacuated Powder Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 300 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION EVACUATED POWDER

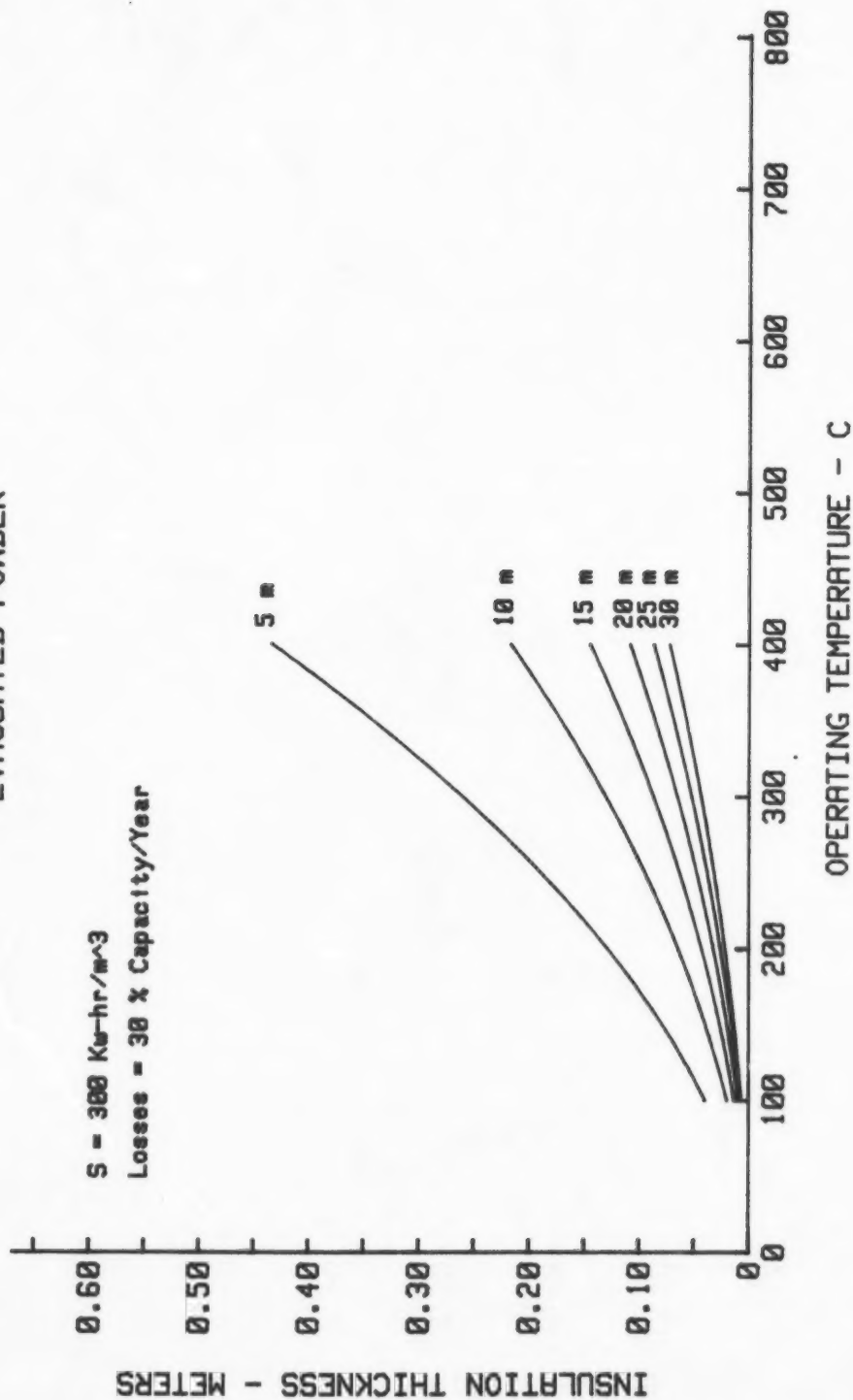


Fig. 18 Thickness of Evacuated Powder Insulation Required for a
 Seasonal Storage with 30% Annual Losses and a Storage
 Media Capacity of 300 Kw-hr/m³

THERMAL ENERGY STORAGE INSULATION ALUMINUM OPACIFIED GLASS FIBER

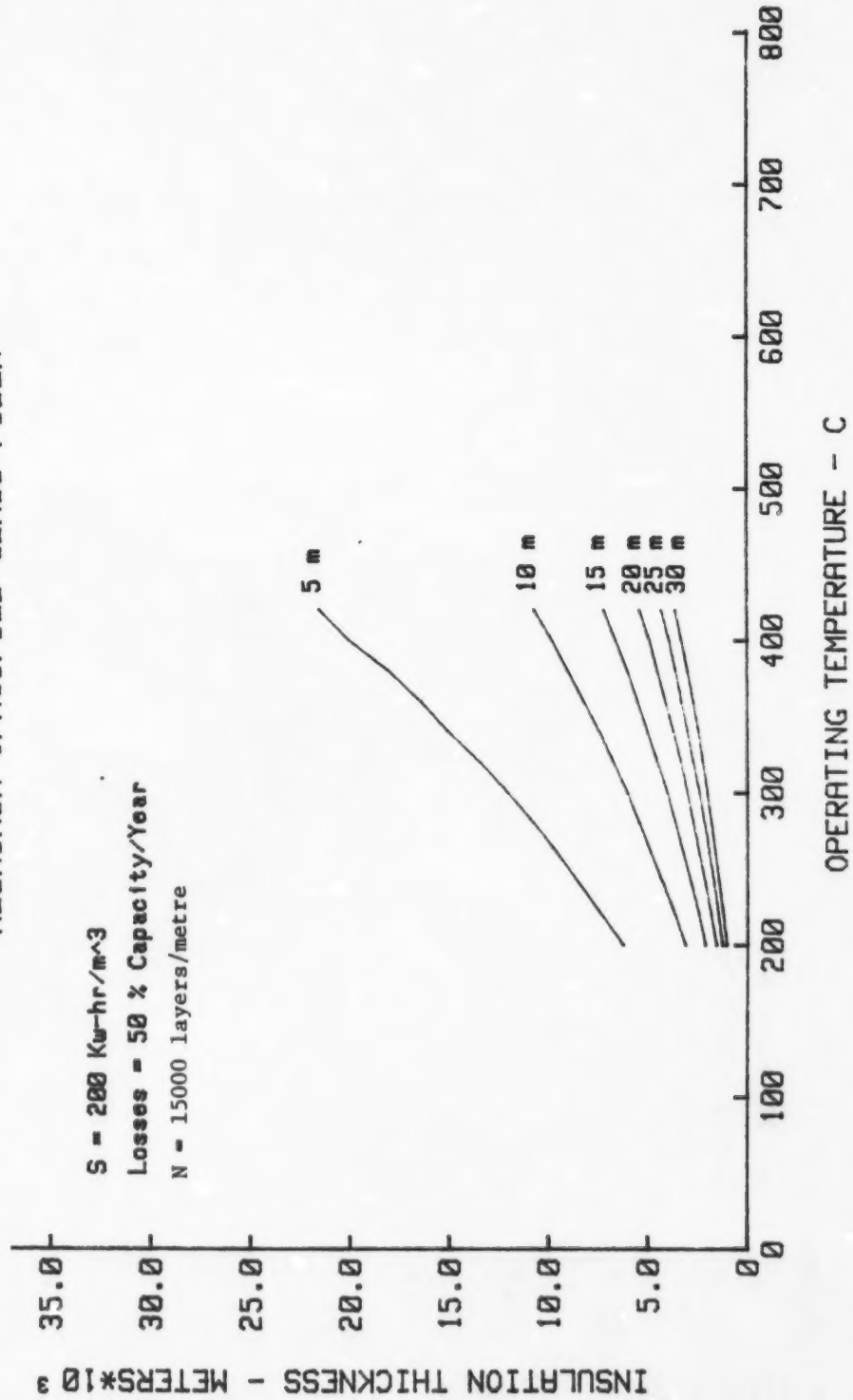


Fig. 19 Thickness of Aluminum Opacified Glass Fiber Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 200 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION

ALUMINUM OPACIFIED GLASS FIBER

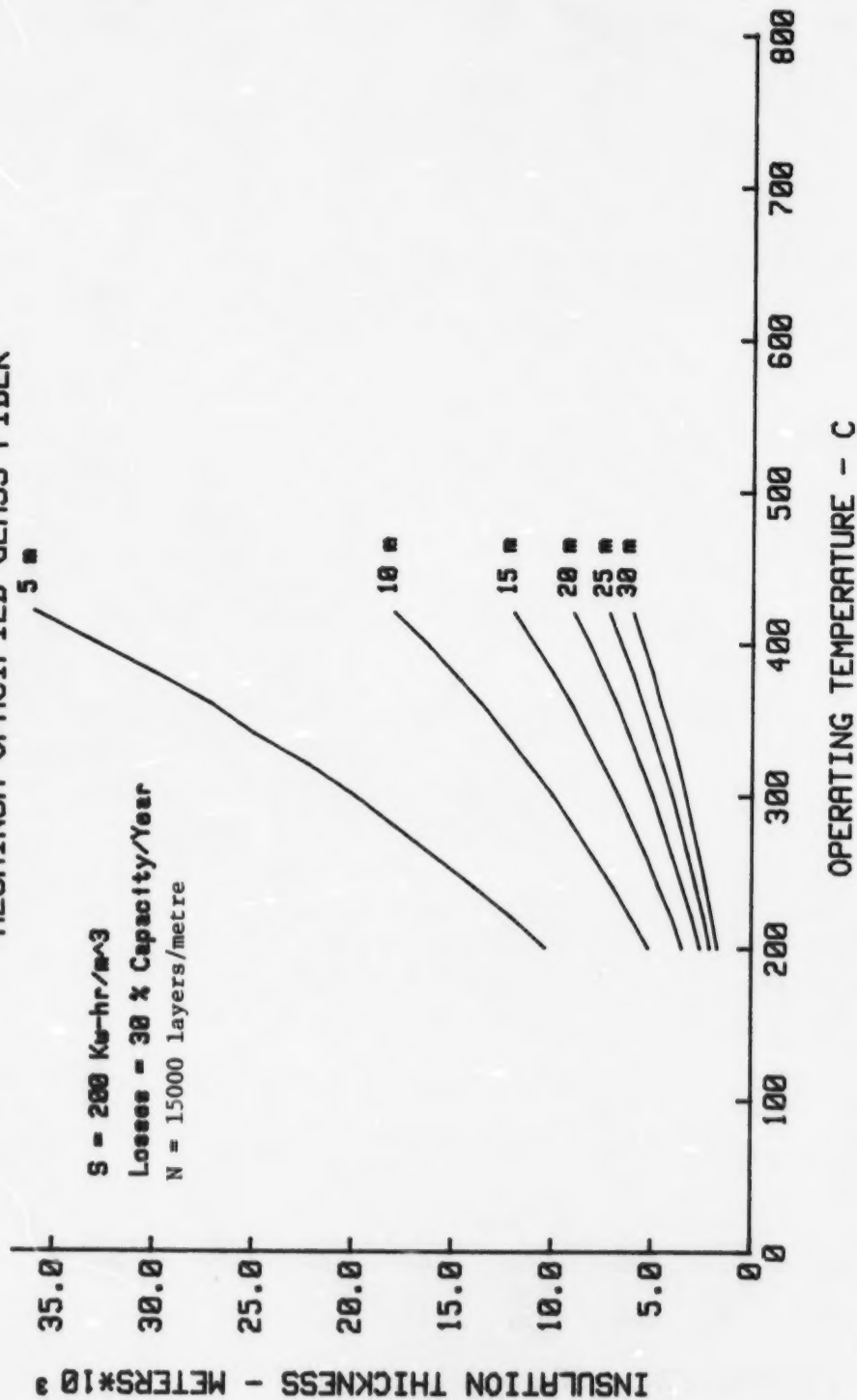


Fig. 20 Thickness of Aluminum Opacified Glass Fiber Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 200 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION ALUMINUM OPACIFIED GLASS FIBER

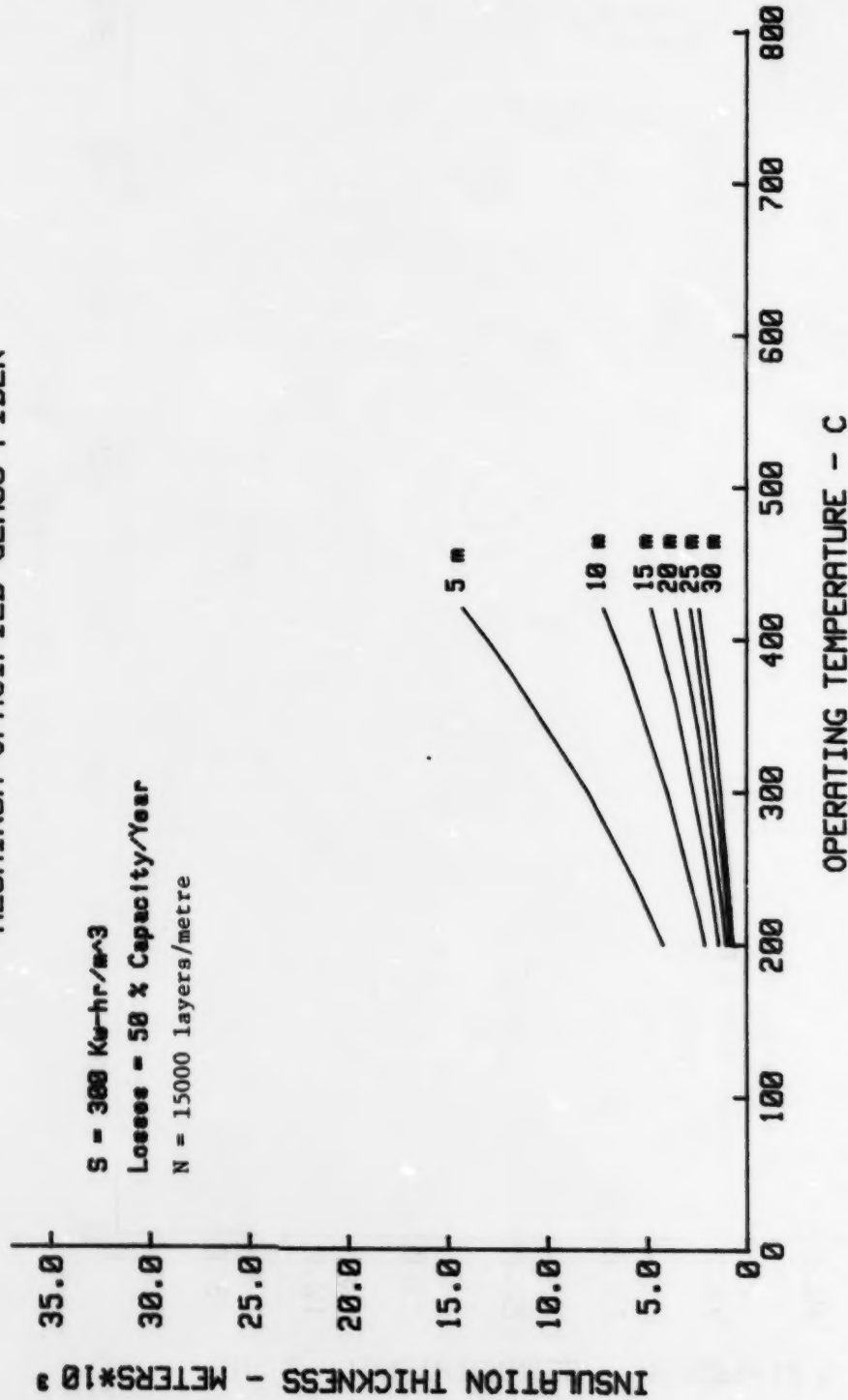


Fig. 21 Thickness of Aluminum Opacified Glass Fiber Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 300 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION ALUMINUM OPACIFIED GLASS FIBER

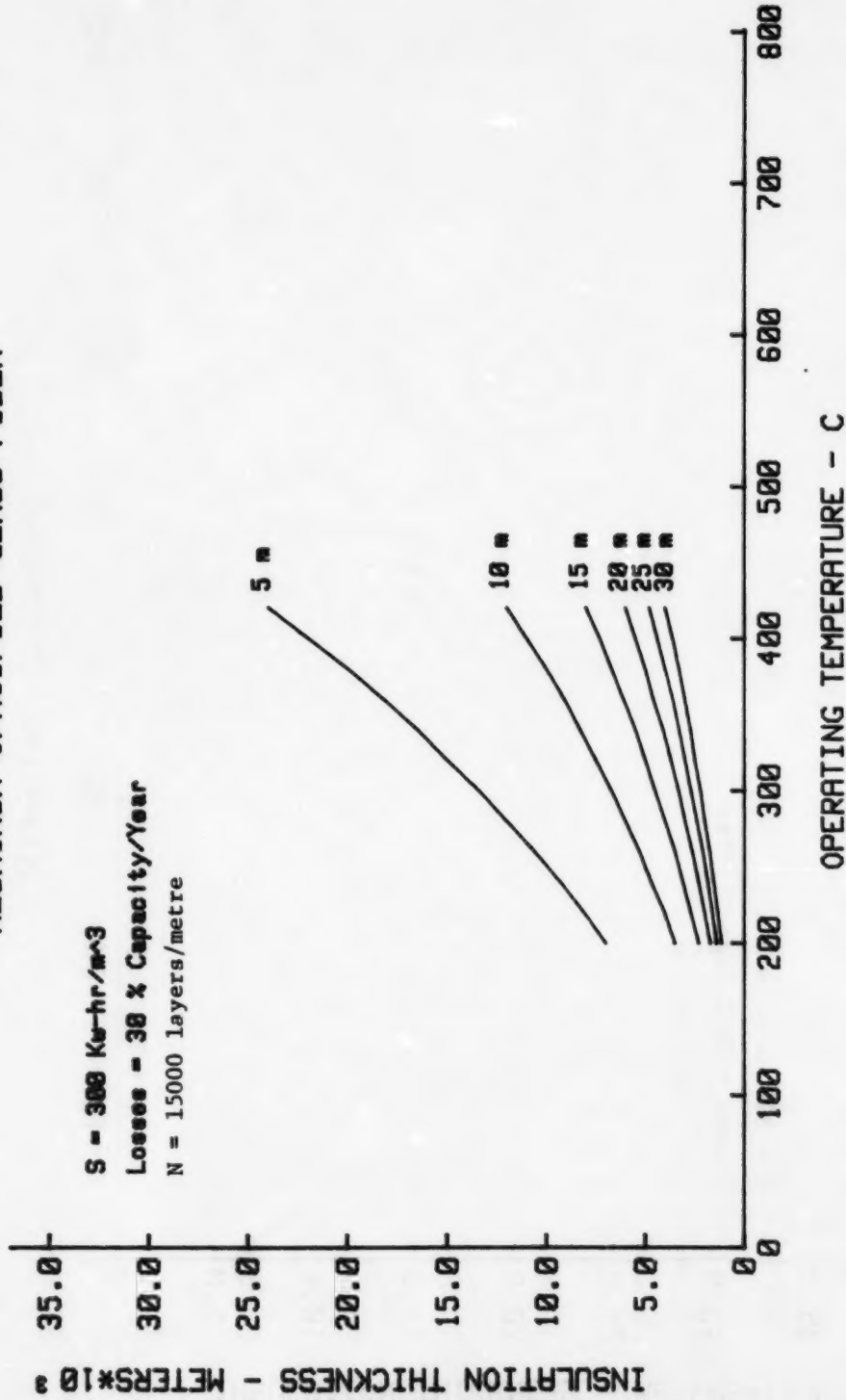


Fig. 22 Thickness of Aluminum Opacified Glass Fiber Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 300 Kw-hr/m³

THERMAL ENERGY STORAGE INSULATION NICKEL OPACIFIED-QUARTZ FIBER

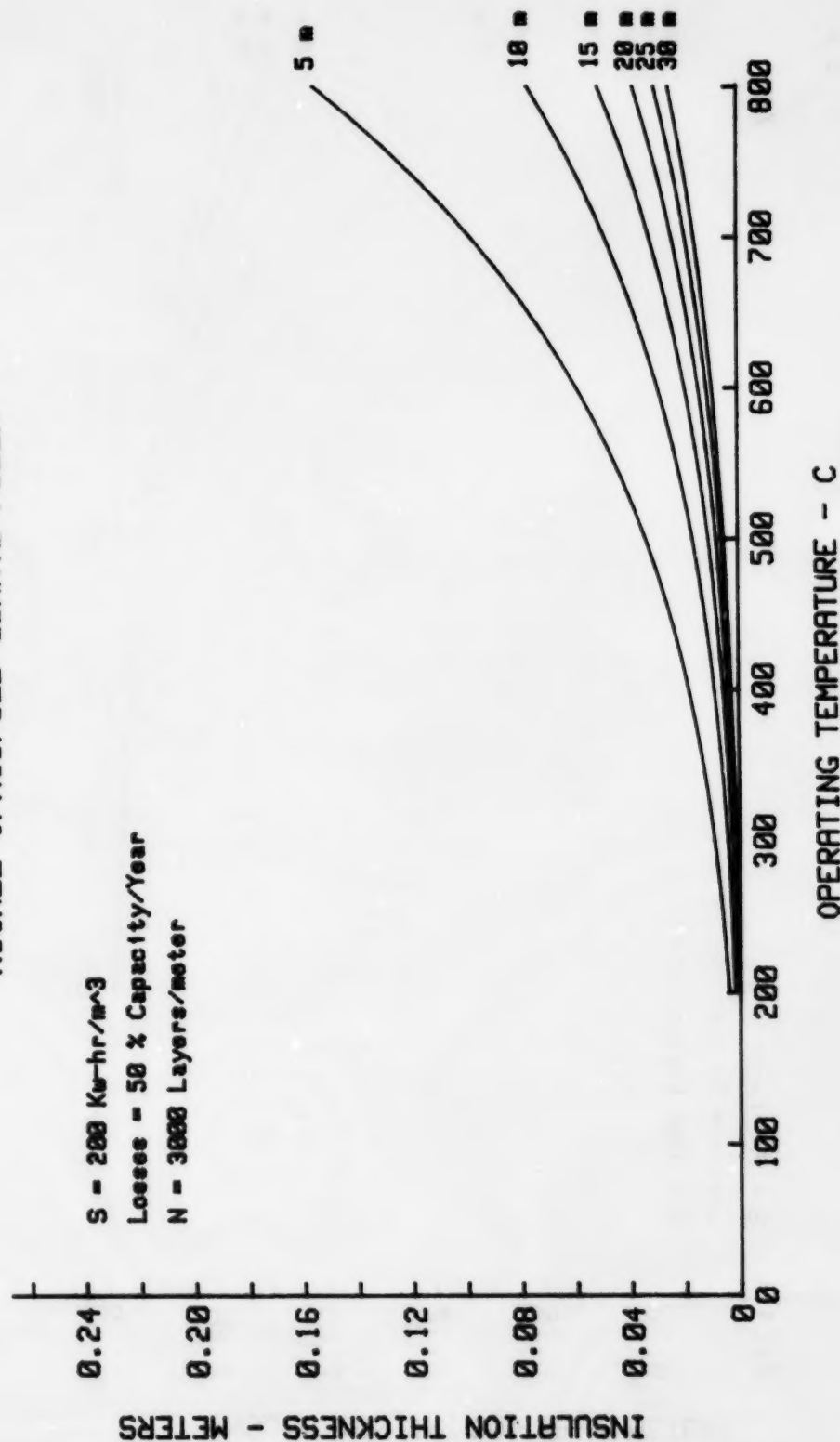


Fig. 23 Thickness of Nickel Opacified-Quartz Fiber Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 200 Kw-hr/m^3

THERMAL ENERGY STORAGE INSULATION NICKEL OPACIFIED-QUARTZ FIBER

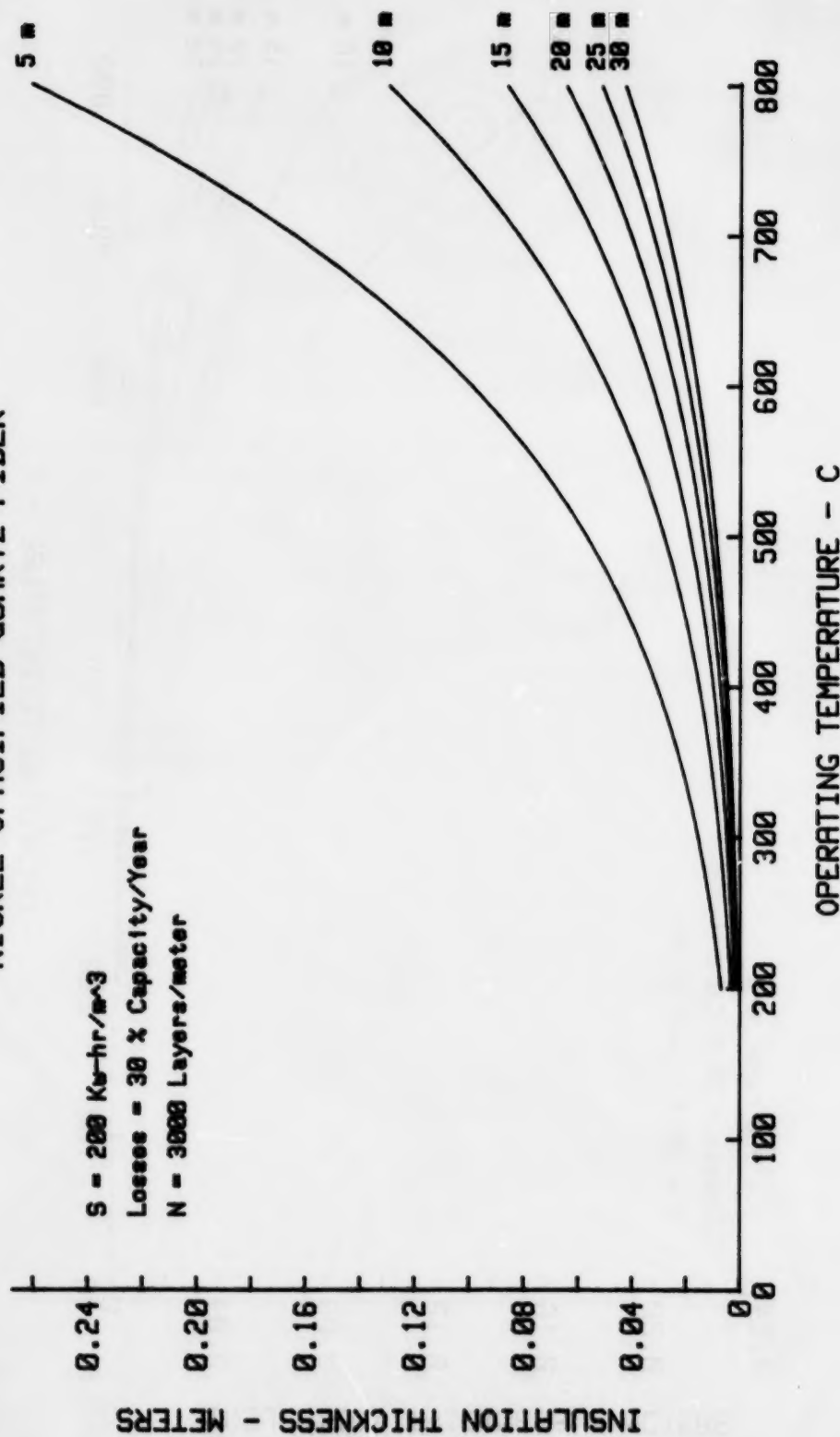


Fig. 24 Thickness of Nickel Opacified-Quartz Fiber Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 200 kw-hr/m³

THERMAL ENERGY STORAGE INSULATION NICKEL OPACIFIED-QUARTZ FIBER

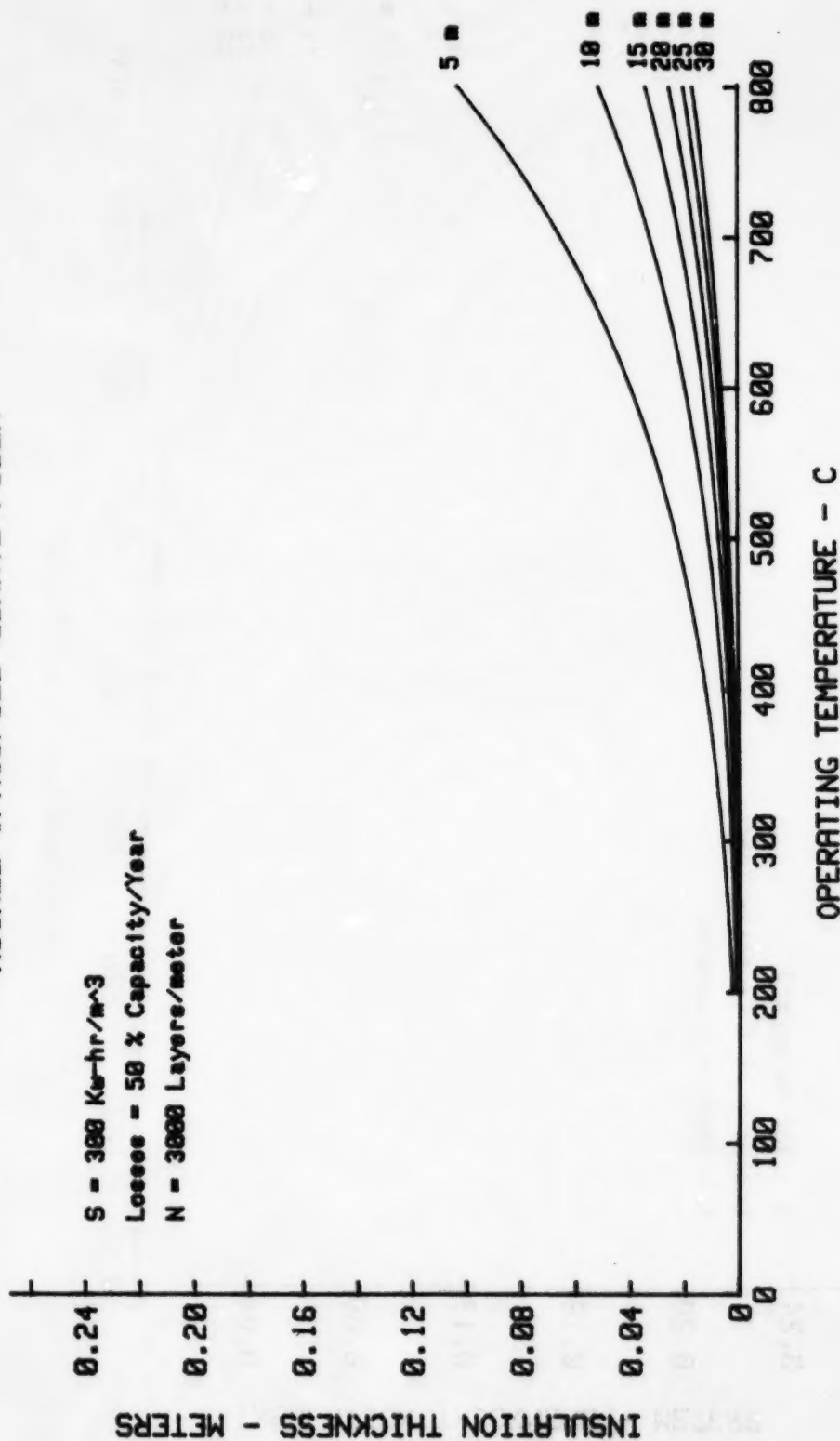


Fig. 25 Thickness of Nickel Opacified-Quartz Fiber Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 300 kW-hr/m³

THERMAL ENERGY STORAGE INSULATION NICKEL OPACIFIED-QUARTZ FIBER

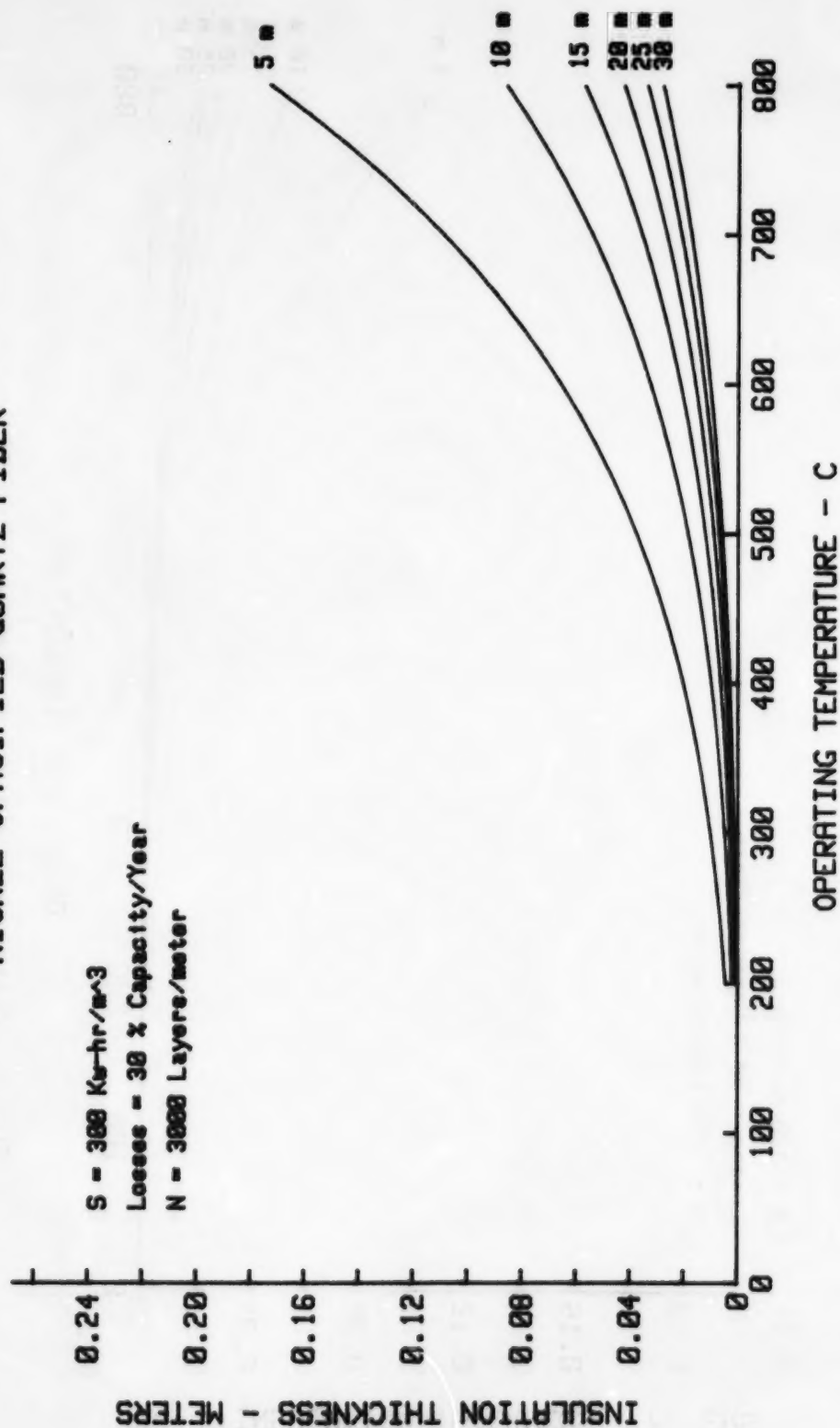
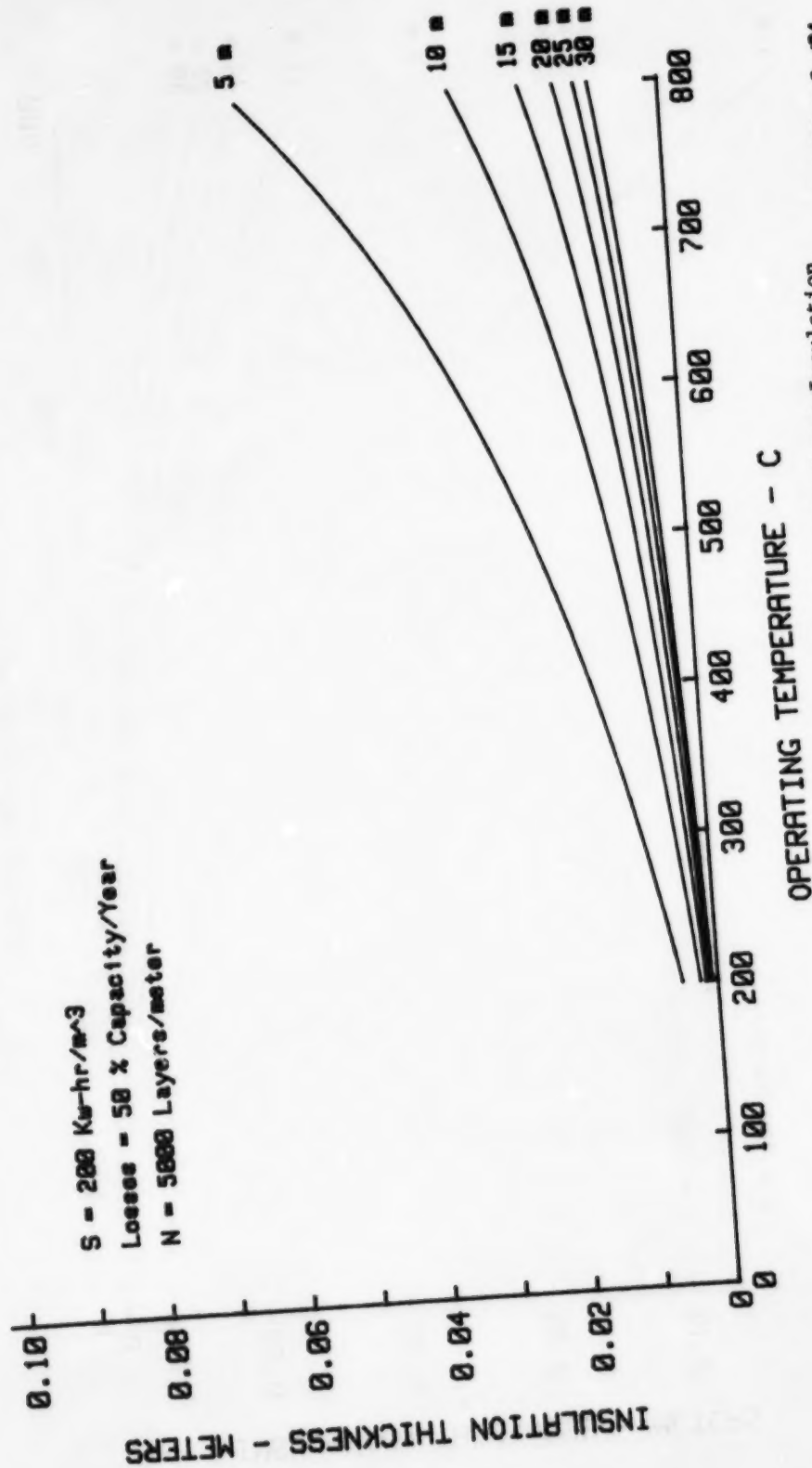


Fig. 26 Thickness of Nickel Opacified-Quartz Fiber Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of $300 \text{ kW}\cdot\text{hr}/\text{m}^3$

THERMAL ENERGY STORAGE INSULATION NICKEL FOIL-REFRASIL QUARTZ PAPER



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Thickness of Nickel Foil - Refrasil Quartz Paper Insulation
Required for a Seasonal Storage with 50% Annual Losses and
a Storage Media Capacity of 200 kw-hr/m³

Fig. 27

THERMAL ENERGY STORAGE INSULATION

NICKEL FOIL-REFRASIL QUARTZ PAPER

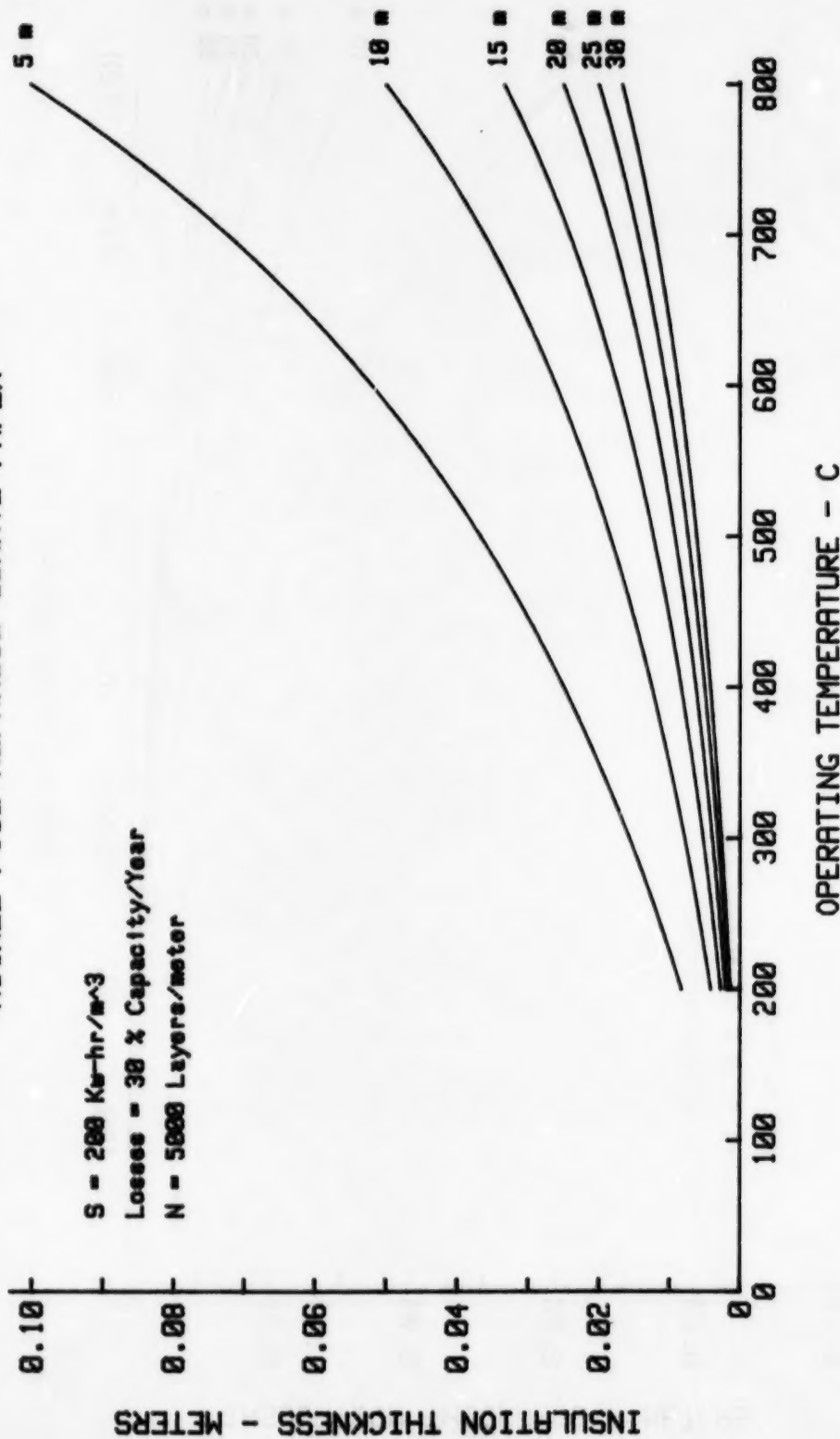


Fig. 28 Thickness of Nickel Foil - Refrasil Quartz Paper Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 200 kW-hr/m³

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THERMAL ENERGY STORAGE INSULATION NICKEL FOIL-REFRASIL QUARTZ PAPER

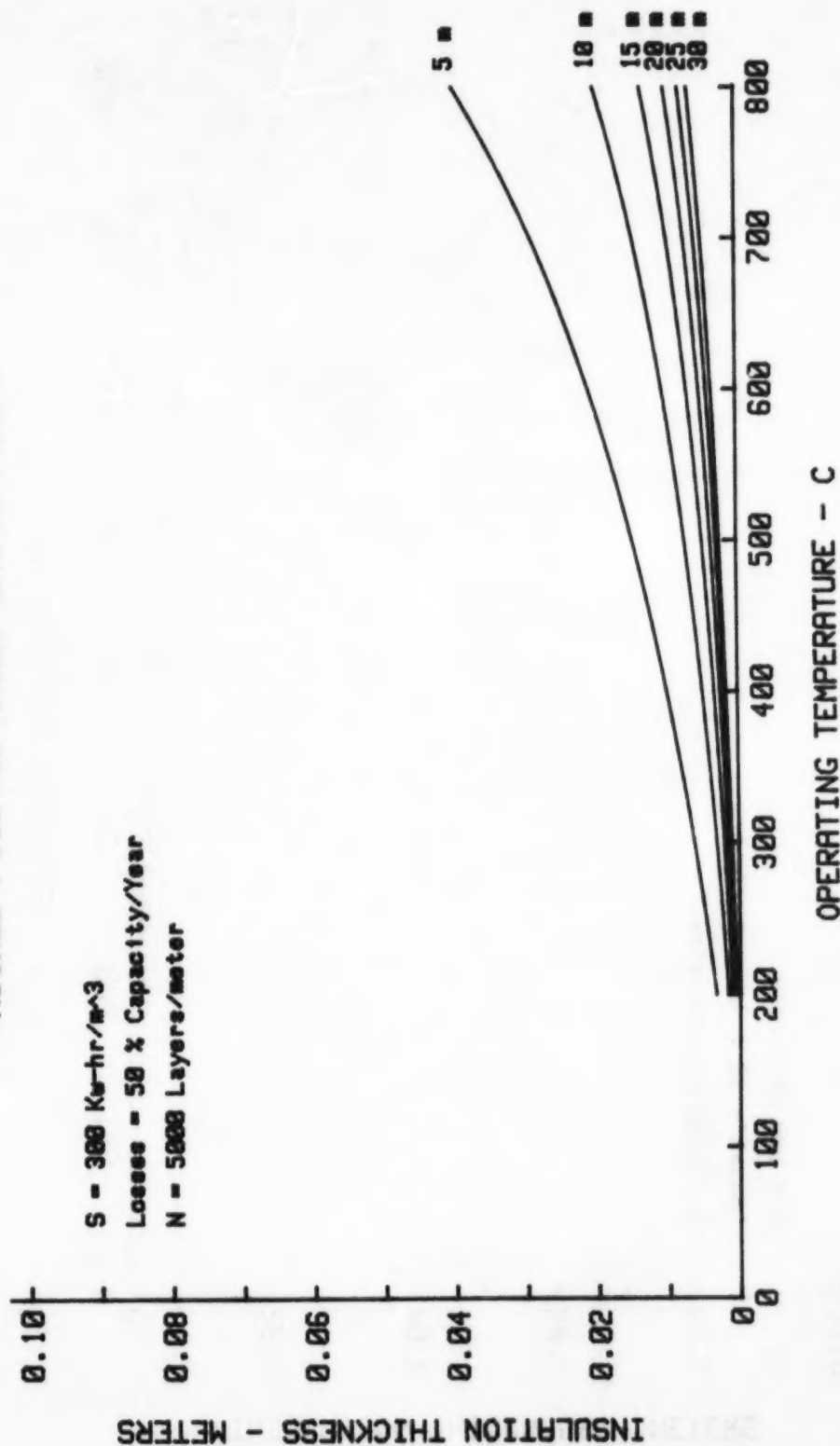


Fig. 29 Thickness of Nickel Foil - Refrasil Quartz Paper Insulation Required for a Seasonal Storage with 50% Annual Losses and a Storage Media Capacity of 300 kw-hr/m³ JPL 24 / 8 / 64

THERMAL ENERGY STORAGE INSULATION NICKEL FOIL-REFRASIL QUARTZ PAPER

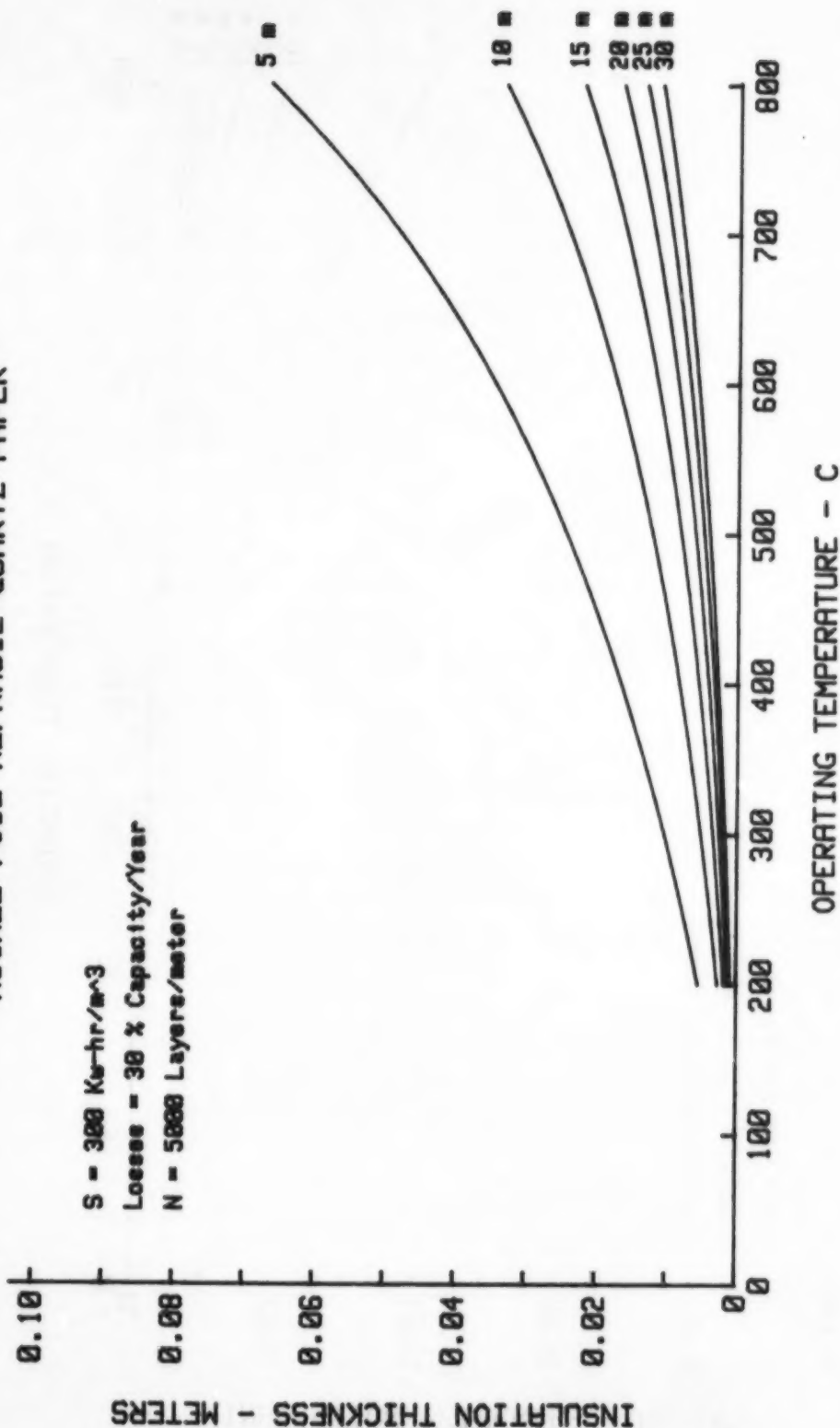


Fig. 30 Thickness of Nickel Foil - Refrasil Quartz Paper Insulation Required for a Seasonal Storage with 30% Annual Losses and a Storage Media Capacity of 300 kW-hr/m³

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TABLE I

OPERATING EFFICIENCIES OF STORAGES
FOR VARIOUS LOSS RATES

<u>Annual Loss</u> % of Capacity	<u>Usable Energy</u> % of Capacity	<u>Collected Energy</u> % of Capacity	<u>Efficiency</u> <u>Usable Energy</u> Collected Energy %
10	95	105	90
20	90	110	82
30	85	115	74
40	80	120	67
50	75	125	60
60	70	130	54
70	65	135	48
80	60	140	43
90	55	145	38
100	50	150	33

TABLE 2

RECOMMENDED MULTI-LAYER VACUUM INSULATION COMBINATIONS

	Foils	Nominal Thickness in.	Spacers
1650°C	Molybdenum	0.0005	Woven Zirconia Cloth
1000°C	Molybdenum	0.0005	Woven Quartz Cloth
900°C			
	Nickel	0.0005	Nickel Opacified Quartz Paper* Woven Quartz Cloth Quartz Paper
		0.0100	
		0.0050	
		0.0050	
800°C			
	Copper	0.0005	Copper Opacified Quartz Paper* Woven Quartz Cloth Quartz Paper
		0.0100	
		0.0050	
		0.0050	
500°C			
	Aluminum	0.00025	Aluminum Opacified Glass Paper* Glass Paper
		0.00300	
		0.00300	
Ambient			

*Fibrous paper, into which metal flakes are introduced for greater radiation attenuation.

Note: This table was extracted from Notaro, Nies and Hedel [Ref.5].

TABLE 3

THICKNESS OF INSULATION REQUIRED TO
INSULATE A 10-METRE DIAMETER STORAGE

Insulation	Thickness - metres			
	Operating Temperature °C			
	200	400	600	800
Glass fibre - no binder	0.81	2.3	4.6	8.1
Alumina-silica fibre + binder	0.41	0.87	1.32	1.77
Foam glass	1.02	2.9	-	-
Evacuated powder + glass fibre	0.10	0.33	-	-
Aluminum opacified glass fibre	0.005	0.016	-	-
Nickel opacified quartz fibre	0.004	0.015	0.049	0.13
Nickel foil + reffrasil quartz paper	0.004	0.012	0.026	0.05

Note: Storage media capacity = 200 kW-hr/m³.
Annual losses = 30% capacity.

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ADDRESS/ADRESSE 16 T. R. Ringer, Head, Low Temperature Laboratory, Division of Mechanical Engineering, National Research Council of Canada, Montreal Road, Ottawa, Ontario. K1A 0R6 (613) 993-2439					